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ASSESSMENT OF ENERGY RECOVERY POTENTIAL OF INDUSTRIAL COMBUSTION EQUIPMENT

by

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of solid and hazardous wastes. These materials, if improperly dealt with, can threaten both public health and the environment. Abandoned waste sites and accidental releases of toxic and hazardous substances to the environment also have important environmental and public health implications. The Hazardous Waste Engineering Research Laboratory assists in providing an authoritative and defensible engineering basis for assessing and solving these problems. Its products support the policies, programs and regulations of the Environmental Protection Agency, the permitting and other responsibilities of State and local governments and the needs of both large and small businesses in handling their wastes responsibly and economically.

The subject of this report is site-specific data on industrial combustion process waste energy, energy requirements for pollution control and the potential for recovery of waste energy. The results are intended to supplement more broadly-based assessments of industrial energy use by providing test data on waste energy and energy consumption by pollution control devices. The work should be of use to researchers engaged in assessment of means to reduce industrial energy consumption and to offset the energy requirements of pollution control. Further information on the subject can be obtained from the Alternative Technologies Division, U.S. Environmental Protection Agency, Cincinnati, OH 45268.

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ABSTRACT

An assessment was conducted to evaluate the waste heat content and energy recovery potential of flue gases from 30 industrial combustion devices. Pollution controls on nine of the devices were evaluated to estimate energy requirements and particulate reduction; energy requirements were compared with flue gas energy recovery potential and particulate reductions were compared with incremental emissions at electric utilities supplying power for the pollution controls. Metal processing furnaces had the highest waste heat content in the exhaust gas (57-86% of fuel heat input). The remaining devices and waste heat content range were: Internal Combustion Engines (21 and 38%), Mineral Kilns (11-55%), Petroleum Process Heaters (14-38%), Boilers (10-41%), and Gas Turbine Combined Cycles (15 and 16%). Energy recovery by combustion air preheat, process heat utilization, or heat engine cycles was evaluated on a preliminary basis and appears to be practical for many of the devices. Energy requirements for particulate emissions control were found to be less than 2.0 percent of heat input. The recoverable energy exceeded pollution control energy in seven of nine cases by a ratio of from 2 to 49. The particulate reduction on a mass basis at the industrial facilities ranged from 7.3 to 23,000 times the incremental mass of total emissions generated at electric utilities supplying power to operate the control equipment.

This report was submitted in partial fulfillment of Contract No. 68-02-2645 by KVB, Inc. under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period September 30, 1977 to December 31, 1982, and work was completed as of February 28, 1983.

LIMITATIONS ON APPLICATION OF DATA REPORTED

The pollution emission and energy data cited in this report represent a small sample of industrial combustion equipment. The data are intended to present the general emission and energy characteristics of each type of equipment tested and the response of that equipment to combustion modifications. Because of the small sample size, application of the data to estimate mean emissions from a class of similar equipment, or to predict emissions from any other single piece of equipment, or for use in establishing emissions standards would be a misapplication.

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- Thermo Electron Corporation
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SECTION 1

INTRODUCTION

OBJECTIVE AND SCOPE

The primary purpose of this study was to determine the energy recovery potential and pollution control energy consumption of industrial combustion devices for which site-specific data had been gathered. The results are intended to serve as specific examples of energy usage and energy recovery potentials of these boilers and process units. It was not intended that broad conclusions could be reached by this study. Rather, the information presented here is intended as supporting material, based on field tests, for more broadly-based assessments of industrial energy consumption and conservation.

The program scope encompassed combustion and emissions data from industrial combustion devices tested under EPA Contracts 68-02-2144 and 68-02-2645 which were assessed to establish energy balances. These devices consisted of petroleum process heaters, mineral kilns, metal processing furnaces, boilers (e.g. wood-bark boilers, carbon monoxide (CO) boilers, black liquor recovery boilers, etc.), internal combustion engines and gas turbine combined cycles.

As an addendum to this field test program, assessments were made to determine the pollution reduction and energy requirements for pollution control equipment over a broad range of operating conditions.

LIMITATIONS OF ANALYSIS

Implementation of any energy recovery system must by made with proper attention to the operational characteristics of the device being modified. These considerations must account for disturbances which are introduced by the energy recovery system into the device, and the device's capability to accommodate these disturbances. Cost, maintenance, and reduced plant availability also must be considered.

At a minimum, the flue gas will undergo an additional pressure loss as it flows through the recovery system heat exchanger. This loss could be supplied, for example, by increasing the output of circulating fans and/or changing damper position. However, a naturally drafted process heater may be very limited in its ability to accommodate an additional pressure loss.

Another matter for concern is the reduction in stack effect due to flue gas cooling (energy recovery). This effect is of significant importance and must be carefully considered to assure proper flue gas flow through atmospheric combustion devices, and subsequent plume rise and dispersion.

The above considerations necessitate the conduct of a detailed analysis for each of the tested devices and for each potential energy recovery method. This step is required to assure satisfactory operation. Device operational parameters may be adversely affected by the energy recovery system.

The pollution emission and energy data cited in this report represent a small sample of industrial combustion equipment. The data are intended to present the general emission and energy characteristics of each type of equipment tested. Because of the small sample size, application of the data to estimate mean emissions from a class of similar equipment, or to predict emissions from any other single piece of equipment, or for use in establishing emissions standards would be a misapplication.

TECHNICAL APPROACH

This section describes the technical plan and methodology used. Additional information presented in this section include a background of the combustion devices tested, calculation procedures and methods of analysis.

Background Information

This study was based on data that was collected from a previous investigation into combustion modifications for 25 industrial combustion devices under EPA Contract 68-02-2144, Ref. 1, and an additional investigation of combustion modifications for NO_x emission reduction on five devices in the current contract, EPA Contract 68-02-2645. These data were used in an evaluation of the following items:

- Waste heat content of the flue gas and recoverable energy
- Energy requirements for air pollution control devices

Table 1 lists the combustion devices included in this study.

The basic data needed to determine the waste heat content of the exhaust gases was available (exhaust gas temperature, composition and mass flow rate) from the test data on the above referenced contracts. Using this heat content of the exhaust gases and the design limits of heat recovery devices, the recoverable energy can be evaluated.

It is important to note that estimates of recoverable energy are dependent on where the flue gas temperature is measured. Air quenching is frequently employed in the ducting between the exit of process furnaces and the entrance to a stack or pollution control device. The purpose of air quenching is to reduce gas temperatures to a level acceptable for the downstream equipment. Also, there may be air leakage or duct surface heat losses that can significantly reduce gas temperatures. These heat losses need to be considered in analysis and use of field data. The optimum data includes temperature at the point where energy recovery equipment would be installed. This point may not be the precise point where temperature measurements are

TABLE 1. COMBUSTION DEVICE SUMMARY

Combustion Device	Location/ Unit-Test*	Fuel	Heat Input, MW	Stack Temp., °K	Pollution Control
Petroleum Process Heaters	4-4	Gas/Oil	30.9	550	No
(Natural Draft)	4-6	Refinery Gas (RG)	31.1	557	No
	5/1	RG	18.5	478	No
	5/2	RG	10.1	481	No
	7/1	RG	15.5	592	No
	7/2	RG	15.1	780	No
	7 (2645)*	Natural Gas (NG)	15.9	693	No
	7 (2645)*	NG/No. 6 Oil	14.3	687	No
(Forced Draft)	12/1-1	RG	22.5	396†	No
	12/1-8	RG/No. 6 Oil	22.5	398†	No
	12/2-1	RG	10.2	563	No
	12/2-2	No. 6 Oil	10.2	556	No
Mineral Kilns					
Clay	1-1	NG	12.4	330†	No
Cement	3-2	Coke	69.9	558†	Multicyclone and Baghouse
Cement	9-1A	NG	61.4	422†	Electrostatic Precipitator
Cement	9 (2645)*	Coal	57.1	494†	No
Lime	6 (2645)*	No. 6	15.6	527†	No

*(2645) indicates devices tested under Contract 68-02-2645, remaining were tested under Contract 68-02-2144.

†This combustion device has an existing heat recovery unit.

TABLE 1. (CONTINUED)

Combustion Device	Location/ Unit-Test*	Fuel	Heat Input, MW	Stack Temp., °K	Pollution Control
Metal Processing Furnaces					
Aluminum	6-1	Natural Gas (NG)	6.5	1211	No
Aluminum	6-3	No. 2 Oil	7.1	1208	No
Steel OH	14-1	NG/No. 6 Oil	30.3	550†	Electrostatic Precipitator
Steel Reheat	16/1-17	NG	24.6	730	No
Steel Soaking Pit	16/2-1	NG	2.3	1583	No
Boilers	10/1-1	Wood/NG	75.3	533†	Multicyclone and Venturi Scrubber
	10/2-2	Black Liquor	140.3	425†	Electrostatic Precipitator
	13-6	Wood/Coal	25.5	478†	Multicyclone
	11-1	CO/RG	94.9	589	Multicyclone
	19-53	No. 2	5.0	543	No
	19-97	No. 6	5.8	527	No
	19-181	NG	5.7	538	No
	200-G-2	NG	11.7	496†	No
	200-24	No. 6	11.2	491†	No
	3 (2645)*	Wood/Coal	29.4	489†	Multicyclone
	5 (2645)*	Wood/Oil	78.0	513†	Multicyclone and Venturi Scrubber
Internal Combustion Engines	2-1	NG	3.2	622	No
	15-1	No. 2 Oil	1.3	475	No
Gas Turbine Combined Cycles	7/3-1	Refinery Gas (RG)	202	456	No
	8-1	RG	519.9	499	No

*(2645) indicates devices tested under Contract 68-02-2645, remaining were tested under Contract 68-02-2144.

†This combustion device has an existing heat recovery unit.

made. This fact introduces a degree of uncertainty in a heat recovery analysis.

A total of nine units tested had pollution-control devices which were tested for particulates either upstream or downstream of the control device. Estimates of the unknown pollutant flow were made based on estimated control efficiencies. This was the preferred method as opposed to incurring the cost for return of field test crews to those sites and to obtain additional information. The energy requirements for the two pollution-control devices in contract 68-02-2645 were determined during the combustion modification test period. The energy requirements for the devices tested under contract 68-02-2144 were determined by revisiting the sites and obtaining the information from the plant.

The objective for selection of test units was to locate units that are representative of current industrial kilns, boilers, process heaters, furnaces, dryers, ovens, stationary internal combustion engines, and gas turbines. The determination was to be made with reference to existing data, and contact with manufacturers and associations. This emphasis on selection of representative units would enhance the widest possible applicability of the program results to many industrial combustion devices.

The scope of the test program provided for tests of about 25 devices. Since there are several thousand industrial combustion devices, it would not be possible to select test units representative of all types of units in current use. The emphasis was therefore placed on selection of units within industries that are most significant in terms of national emissions of criteria pollutants (NO_x, SO_x, CO, HC, and particulates) and energy consumption.

The data used in unit selection were gathered from the U.S. EPA, including the computerized National Emissions Data System (NEDS), various contractor reports, equipment manufacturers, associations of manufacturers, and equipment operators.

With regard to industrial boilers, the survey was restricted to boilers that operate with unconventional fuels, such as CO gas, wood and black liquor. Industrial boilers burning the conventional fuels (natural gas, fuel oil and coal) have been examined in detail in previous studies (References 2 and 3).

All criteria pollutant emissions were considered. However, the fact that NO_x emissions are generally most amenable to reduction by combustion modifications leads to an emphasis on devices that are high in NO_x emissions.

Results of a survey of industrial combustion equipment are presented in detail in Reference 1. Industries identified as having combustion equipment that are significant in terms of energy and emissions, ranked by NO_x emissions are shown in Table 2.

TABLE 2. SIGNIFICANT ENERGY-CONSUMING INDUSTRIES RANKED BY NO_x EMISSIONS*

Industry	Combustion Device
Petroleum refining	Process heaters
Wood pulp and pulp board	Wood waste boilers Black liquor recovery boilers
Portland cement	Rotary kilns
Chemical	Charcoal retorts Ammonia reformers
Iron and steel	Open hearth furnaces Soaking pits Reheat furnaces Coke ovens Blast furnaces Heat treating furnaces
Glass containers	Melting furnaces
Various industries	Reciprocating engines Gas turbines

*Industries and devices are listed in order of decreasing national (U.S.) NO_x emissions.

Information regarding each equipment type was gathered, as available, with regard to:

1. Major manufacturers
2. Associations
3. Basic equipment and combustor design
4. Current fuel use, trends and properties
5. Trends in equipment type, age, size and use
6. Total number and geographic distribution
7. Limitations in equipment uses and fuels
8. Quantity and geographic distribution of fuels used
9. Air pollutant emissions

The emission measurements were performed as reported in Reference 1. Gaseous emissions were measured using analytical instruments and equipment contained in a government-furnished mobile instrumentation laboratory. Total particulate measurements were made using an EPA Method 5 sampling train. Particulate size distribution was made using either an Andersen 2000 Cascade Impactor or a Brink Model B Cascade Impactor depending upon the grain loading. Further details of the sampling methods are given in Reference 1.

Prior to a test, the test site was inspected to determine equipment location, sample acquisition points, pertinent unit operational instruments and recording units, and specific combustion modifications to be performed. Tests were outlined with unit operating personnel.

Most tests, excluding trace species and organics sampling, were accomplished in four to six days. The initial day was devoted to test equipment set-up, coordination with the unit operating personnel, a thorough review of instruments, process and operational characteristics, and initiation of sampling for baseline operational and emissions data.

Following baseline data acquisition, the proposed combustion adjustments were implemented individually. All unit operational and emissions data were recorded for each adjustment implemented. Fuel samples were obtained at pertinent points during the test period.

Calculation Procedure

Waste Heat Content of Exhaust Gases and Recoverable Energy--

The waste heat content of the exhaust gas was determined at stack temperature relative to 298 K (77°F) with moisture in the flue gas condensed. This definition is consistent with the definition of fuel higher heating value. Recoverable energy is defined as the portion of waste heat content which is recoverable by practical methods. Appendix A contains sample calculations of the waste heat content and recoverable energy.

At the particular sampling point where the information on temperature, composition and velocity was measured and recorded, the actual volumetric

flows were calculated for each case. Then using the composition of the flue gas, the waste heat content was calculated at the temperature of the sampling point from the Gas Tables prepared by Keenan and Kaye (Ref. 4). Also, the percentage recoverable energy as noncondensible and waste heat content as a percent of fuel heat input were calculated.

Each combustion device was examined to determine if energy recovery is practical, what recovery methods might be employed, and the amount of recoverable energy that should be achievable.

Options for waste heat recovery that were considered are:

- Combustion air preheating
- Process heat utilization
- Thermodynamic heat engine cycles

For combustion air preheating and process heat utilization (hot water or steam), a minimum practical exit gas temperature of 400 K (260°F) was used based on conservative application of limits recommended by a major heat recovery equipment manufacturer (Ref. 5) and assessment of the units already equipped with heat recovery that were included in this study. A temperature of 400 K is sufficiently high to avoid corrosion from sulfuric acid condensation for most any fuel burned with up to 5 percent fuel sulfur. Although lower temperatures might be suitable for natural gas or low sulfur distillates, the need for ability to burn a wide range of fuels constrains the ability to design for lower temperatures. This minimum value also allows for low cold-end temperatures when the device operates at partial load. The energy recovery potential may be equal for these two types of recovery devices but there are several factors which influence a choice of one over the other. First, their optimum effectiveness will differ. Second, the ease of utilization of the recovered heat varies considerably from plant to plant. Third, the capital costs of these two techniques are not the same.

For the combustion air preheat option, the ability to cool the exhaust gases to 400 K is limited by the fact that the combustion air flow and the flue gas are of approximately equal mass flow (the flue gas flow is slightly higher due to the fuel products and leakage). The amount of heat that can be transferred from the flue gas to the air is limited by the practical size of the air preheater. The relations between heat transferable and preheater size, given in Reference 6, involve an "effectiveness", ε, as related to number of transfer units (NTU). Effectiveness is defined as the ratio of actual heat transfer to maximum possible heat transfer. Number of transfer units is a non-dimensional heat transfer area, AU/C_{min}, where A is area, U is the overall heat-transfer coefficient, and C_{min} is the product of mass flow and specific heat for the fluid which would undergo maximum temperature difference (normally that fluid which has the lower flow rate). Figure 1 shows the relationship between effectiveness and NTU for a cross-flow heat exchanger with fluids unmixed (Ref. 6). When the ratio of C_{min}/C_{max} is near 1.0, as is the case for an air preheater, an effectiveness of 0.7 is a reasonable upper limit for a practical heat exchanger. Larger areas (higher NTU) do not appreciably increase the effectiveness. Therefore, an effectiveness of 0.7

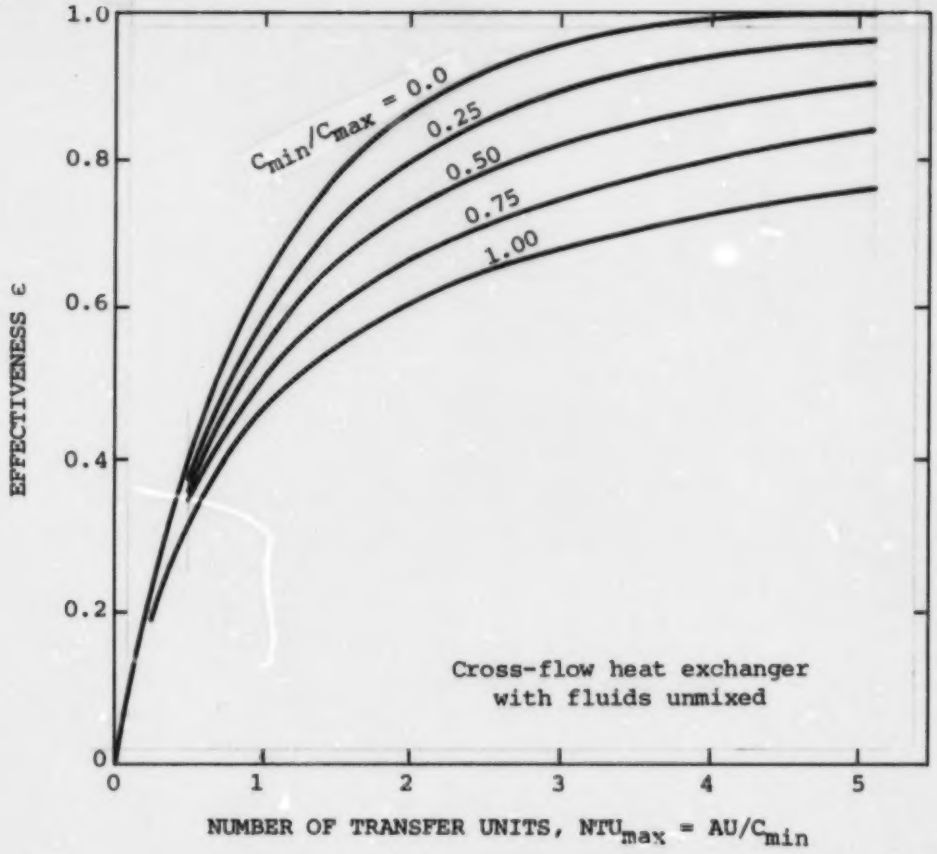

Figure 1. Heat Exchanger Effectiveness versus Number of Transfer Units

has been used in this study as a practical design limit in assessing the recoverable energy by combustion air preheat. This inherent limit on the practical rate of heat transfer will, in most cases, result in a flue gas exit temperature that is well above the 400 K minimum established from dew point considerations.

The air preheater effectiveness is defined by the equation

$$\varepsilon = \frac{(t_{out} - t_{in})}{(T_{IN} - t_{in})} = \frac{\text{Actual Heat Transfer}}{\text{Maximum Possible Heat Transfer}}$$

where

ε = the effectiveness (dimensionless parameter)

t_{out} = the temperature out of preheated air, K (°F)

t_{in} = the temperature in of air, K (°F)

T_{IN} = the temperature of flue gas entering preheater, K (°F)

The relationship was solved for t_{out}. Using the calculated t_{out}, the energy recoverable in the air preheater (q_{rec}) was calculated by the equation

$$q_{rec} = \dot{m}_a \, c_{p_a} \, (t_{out} - t_{in}) = \dot{m}_f \, c_{p_f} \, (T_{IN} - T_{OUT})$$

where q_{rec} is the recoverable energy for the assumed ε in MW (Btu/hr), $\dot{m}$ is mass flow and c_p is specific heat of air (a) and flue gas (f). This q_{rec} was then used to find the temperature of the flue gases leaving the air preheater, T_{OUT}. If T_{OUT} was below the minimum limit of 400 K, then 400 K was used to recalculate q_{rec}, implying use of a preheater with an effectiveness of less than 0.7. The term q_{rec} as defined above assumes no heat loss, i.e., adiabatic conditions and 100 percent heat transfer "efficiency." The use of effectiveness is an alternate procedure to the more conventional "Log Mean Temperature Difference" procedure for heat exchanger design (Ref. 6).

It must be noted that for internal combustion engines and gas turbine combined cycles, air preheat was not a practical method because of unacceptable operational difficulties, e.g., preignition in carbureted internal combustion engines and adverse thermodynamic/material effects in gas turbines.

For the process heat option as compared with the air preheat option, there is greater flexibility in the design of the heat exchanger, because the flow rate of the fluid receiving heat from the flue gas is not fixed. The system designer is free to select the fluid and size the flow rate to optimize the design for any specific system. As can be seen in Figure 1, the

effectiveness can be increased at constant NTU by reducing the ratio C_{min}/C_{max} toward zero. If the flow rate of cold fluid, water for example, were increased well above the flow rate of the flue gas, a heat exchanger could be sized for an effectiveness approaching 1.0. Design for low pressure steam generation would further enhance the heat recovered. In view of this greater flexibility, cooling the flue gas to 400 K is a realistic design goal. Detailed assessment of all the possible uses of process heat as hot water or steam was beyond the scope of this program. Therefore, a fixed level of 400 K for the flue gas exit temperature was used for all calculations of recoverable energy by the process heat option.

For the heat engine cycle option, contact was made with three firms involved in the development and demonstration of organic Rankine cycles. A major consideration in these cycles is the working fluid. One system using toluene has an estimated thermal efficiency of 23 percent (Ref. 7). Another system uses fluorinal 85, a mixture of 96.9 wt % trifluoroethanol and 3.1 wt % water and has an estimated thermal efficiency of 25 percent recoverable energy. A third system uses a low boiling fluorocarbon, has a thermal efficiency of 20 percent and has low inlet flue gas temperature requirements. It was decided to use 22 percent recovery figure as an average and apply a cost/kW value of $2000/kW output (installed) as a generally conservative figure, based on discussions with vendors. The actual design of a unit is highly dependent on the particular specifications of the manufacturer and system requirements and the type of detailed analysis is beyond the scope of this study.

Temperature requirements for the heat engine operation were determined as follows. The minimum inlet flue gas temperature varies considerably with the organic fluid and equipment design and a value of 533 K (500°F) was used as being typical. The exhaust gas temperature limitation for the heat engine itself was taken to be 416 K (290°F).

Recovery analysis--The choice among potential heat recovery techniques is based on two primary criteria:

- economics -- installed capital cost, annual fuel savings
- utilization -- use for energy recovered

Both factors are important and each limitation must be satisfied. The economic decision is based on both capital requirement and return on investment through fuel savings. The ability to use the recovered energy is based on the need to have a demand for the recovered energy at the combustion unit or elsewhere at the facility.

In addition to these two primary criteria, any effect on emissions may influence the selection. In cases where the air preheater option has similar economic and utilization characteristics as another recovery technique, but might increase NO_x due to higher combustion air temperature, the technique with no increase in emissions would have the advantage of not causing air pollution impacts. This may be a particularly important consideration if the NO_x increase is large and the unit is in a non-attainment area. From an

industry's point of view, the only disadvantage of increased NO_x is that the combustion unit will have to be repermitted if the increase in NO_2 is over the threshold value.

Each of the combustion units tested was reviewed to determine which of the above mentioned methods of waste heat utilization offers potential for practical heat recovery. In all cases the lower limit of recoverable energy was taken to be 0.5 MW as this was considered a reasonable value to warrant capital expenditures, based on discussions with vendors.

In determination of the practicality of energy recovery, an important factor is the degree of fluctuation in industrial device operation. Some devices operate continuously with very steady conditions. Petroleum process heaters and carbon monoxide boilers are such devices. Other devices are operated with batch feeding over a set operating cycle. Metal melting furnaces are of this type. Still other devices are tied to an industrial process that is of an inherently fluctuating nature. Cement kilns, and paper mill boilers have constantly fluctuating operation dependent on the feed material properties and on process control adjustments.

The installed costs and fuel savings projected are simple first-order estimates and are presented to show relative economic merits rather than a complete return on investment decision process. For these preliminary assessments, operating and maintenance costs have not been considered. With the wide variation in economic decision models used by industry and fluctuation in the cost of money, these criteria provided a "first look."

The basis for the fuel savings are:

- 8,000 hours/year
- electricity - \$0.08/kW-h ($80/MW-h)
- natural gas - $5/$10^6$ Btu ($17/MW-h)
- No. 6 oil - $8/$10^6$ Btu ($27/MW-h)
- coal - $3/$10^6$ Btu ($10/MW-h)

The installed cost models used were the following, based on 1982 dollars:

- Combustion Air Preheating (Ref. 8):
  Cost, \$ = \$46,000 (MW Fuel Heat Input)$^{0.6}$
- Process Heat Utilization (Ref. 9):
  Cost, \$ = \$37,000 (MW Heat Recovered) + \$67,000 (MW Recovered)$^{0.44}$
- Heat Engine Cycle (Ref. 7):
  Cost, \$ = \$2 x 10^6 (MW Electrical Output)

The yearly savings in fuel cost for all but the heat engine cycle was calculated by:

Fuel Savings/Year, \$ = (8000 h) (MW Heat Recovered) (Fuel Cost, \$/MW-h)

For the heat engine option, the annual savings in fuel cost was determined from:

Fuel Savings/Year, $ = (8000 h) (MW Electrical Output) (Electricity Cost, $/MW-h)

Energy Requirements for Pollution Control Devices--

The energy requirements for the pollution control devices were determined for the in-plant energy consumption. This term is generally referred to as the direct energy consumption for pollution control devices as opposed to the indirect associated with manufacturing the device itself and the chemicals required in its use.

The in-plant energy requirement is made up of the direct energy consumption due to the pressure drop across the device and the peripheral equipment energy requirement associated with pumps, waste removal and disposal.

The emissions reductions were calculated from either upstream or downstream emissions measurements with the actual reduction based on the estimated device efficiency. The reduction in pollutants at the plant was compared with the emissions generated at the power plant due to the electrical energy requirement of the control device. The power plant emissions were then compared with the in-plant emission reduction to evaluate the effectiveness of the control device with respect to the emissions generated at the power plant.

The energy requirements for pollution control were also compared with the recoverable energy for each of the combustion units analyzed.

SECTION 2

SUMMARY AND CONCLUSIONS

WASTE HEAT CONTENT AND RECOVERABLE ENERGY

Table 3 summarizes the waste heat content and recoverable energy for the 30 industrial devices. The fuel heat input tabulated for each device is based on the higher heating value of the fuel burned and the fuel flow rate. The waste heat content of the gas gases at the stack temperature relative to 298 K (77°F) is as a percent of the fuel energy input. The recoverable energy is the portion of waste heat content that is recoverable by practical heat recovery devices and is shown in the table as recoverable energy in MW for the three energy recovery methods considered in this study.

The metal processing furnaces show the highest stack temperatures, and waste heat content. Metal furnace waste heat content ranged from 57 to 86 percent of fuel input. This indicates the need to evaluate this grouping of combustion devices for implementation of energy recovery techniques. The other combustion devices tested had significantly lower waste heat content at 10 to 45 percent. One of the gas turbine combined cycles and a CO-gas-fueled boiler were the units with highest absolute recoverable energy, although these units were lower compared to metal furnaces in terms of recoverable energy as percent of fuel heat input.

For 22 of the 30 devices, recoverable energy ranged from 0.6 to 17.4 MW. The energy recovery technique providing the highest recovery was the process heat option in 20 cases and was air preheat in two cases. For 7 of the devices, energy recovery was not applicable, as the result of low gas temperatures or because the recoverable energy is less than 0.5 MW.

Petroleum Process Heaters-Natural Draft

The stack temperature for the six natural draft petroleum process heaters ranged from 478 K to 780 K. The waste heat content ranged from 13.9 percent to a high of 38.4 percent. The recoverable energy by process heat ranged from 3.6 percent to 21.9 percent of heat input for five heaters. For one heater, the recoverable energy was less than 0.5 MW.

Petroleum Process Heaters-Forced Draft

The stack temperature for the two forced draft heaters ranged from 546 K to 606 K. The waste heat content ranged from 16.0 percent to 35.3 percent. Heater 12/1 has potential for 6.1 to 8.2 percent recoverable energy. This is in addition to an existing air preheater. Heater 12/2 has an 8.2 percent recoverable energy when firing refinery gas and 7.6 percent when firing No. 6 oil. The process heat option was the most favorable for both heaters. However, the air preheat option was almost as favorable.

TABLE 3. SUMMARY OF WASTE ENERGY RECOVERY ANALYSIS

Combustion Device	Location/ Unit - Test	Fuel*	Fuel Heat Input, MW	Stack Temp., K	Waste Heat Content, %	Technically Applicable Energy Recovery Techniques Recoverable Energy, MW		
						Air Preheat	Process Heat	Heat Engine
Petroleum Process Heaters	4	Gas/Oil	30.9	550	24.3	2.1	2.4	(0.5)
(Natural Draft)	4	RG	31.1	557	24.1	2.2	2.3	(0.5)
	5/1	RG	18.5	478	20.5	0.7	0.7	--
	5/2	RG	10.1	481	13.9	(0.3)	(0.3)	--
	7/1	RG	15.5	592	27.1	1.4	1.7	(0.3)
	7/2	RG	15.1	780	38.4	2.5	3.3	0.7
	7 (2645)	NG	15.9	693	25.2	1.8	2.2	(0.5)
	7 (2645)	NG/No. 6	14.3	687	23.5	1.6	2.0	(0.4)
(Forced Draft)	12/1-1	RG	22.5	606	20.4	2.8**	1.9	(0.4)
	12/1-8	RG/No. 6	22.5	546	16.0	3.1**	1.4	(0.3)
	12/2-1	RG	10.2	563	35.3	0.6	0.9	(0.2)
	12/2-2	No.6	10.2	556	20.6	0.7	0.8	(0.2)
Mineral Kilns								
Clay	1-1	NG	12.4	300	11.3	--	--	--
Cement, Dry Process	3-2	Coke/NG	68.9	558	12.9	--	3.2	0.6
Cement, Wet Process	9-1A	NG	61.4	422	55.0	--	0.9	--
Cement, Wet Process	9 (2645)	Coal	57.1	455	45.7	--	2.2	--
Lime	6 (2645)	No. 6	15.6	527	18.8	--	1.4	--
Metal Processing Furnaces								
Aluminum Melter	6-1	NG	6.5	1211	60.6	1.5	2.8	0.6
Aluminum Melter	6-3	No. 2	7.1	1208	61.5	2.2	3.4	0.7
Steel Open Hearth	14-1	NG/No. 6	30.3	550	60.0	--	--	--
Steel Reheat	16/1-17	NG	24.6	730	56.8	2.6	8.4	1.8
Steel Soaking Pit	16/2-7	NG	2.3	1583	86.3	1.0	1.7	0.4

(continued)

*RG = Refinery Gas, NG = Natural Gas, Blk Liq. = Black Liquor, CO = Carbon Monoxide

( ) = Recoverable energy less than 0.5 MW.

-- = Temperatures too low for recovery.

** = This heat recovery method is an existing installation.

TABLE 3. (CONTINUED)

Combustion Device	Location/ Unit - Test	Fuel*	Fuel Heat Input, MW	Stack Temp., K	Waste Heat Content, %	Technically Applicable Energy Recovery Techniques Recoverable Energy, MW		
						Air Preheat	Process Heat	Heat Engine
Boilers	10/1-1	Wood/NG	75.3	533	40.9	6.5	7.5	--
	10/2-2	Blk Liq.	140.3	425	23.4	--	--	--
	13-6	Wood/Coal	25.5	478	22.4	1.1	1.2	--
	11-1	CO/RG	94.9	589	51.0	6.1	16.7	3.4
	19-53	No. 2	5.0	543	23.5	(0.3)	(0.3)	(0.1)
	19-97	No. 6	5.8	527	15.1	(0.3)	(0.3)	--
	19-181	NG	5.7	538	24.8	(0.3)	(0.3)	(0.1)
	200-G-2	NG	11.7	496	10.2	(0.5)	(0.4)	--
	200-24	No. 6	11.2	491	12.9	0.6	(0.4)	--
	3 (2645)	Wood/Coal	29.4	489	17.1	1.3	1.5	--
	5 (2645)	Wood/Oil	78.0	513	19.5	6.6	4.9	--
Internal Combustion Engine	2-1	NG	3.2	622	38.2	--	(<0.5)	(<0.5)
	15-1	No. 2	1.3	475	21.4	--	(<0.5)	--
Gas Turbine Combined Cycles	7/3-1	RG	202	456	15.3	--	4.3	--
	8-1	RG	519.9	499	16.1	--	17.4	--

*RG = Refinery Gas, NG = Natural Gas, Blk Liq. = Black Liquor, CO = Carbon Monoxide

( ) = Recoverable energy less than 0.5 MW.

-- = Temperatures too low for recovery.

** = This heat recovery method is an existing installation.

Mineral Kilns

The stack temperatures for the five mineral kilns ranged from 300 K to 558 K. The waste heat content for the three kilns that operated for a dry process ranged from 11.3 percent to 18.8 percent and the two wet process cement kilns had waste heat content of 45.7 percent and 55.0 percent due to the high water content of the flue gas. In one case the recoverable energy was zero due to the low stack temperature and at the four other sites the recoverable energy ranged from 1.4 to 8.7 percent by process heat recovery.

Metal Processing Furnaces

This group of four combustion devices have the highest stack temperatures, greatest waste heat content and greatest recoverable energy. The stack temperatures ranged from a minimum of 550 K to a maximum of 1583 K. The waste heat content ranged from a minimum of 56.8 percent to a maximum of 86.3 percent. The recoverable energy ranged from 34.3 percent to 75.8 percent. In every case the process heat option appears more favorable, but it must be noted that metal processing units are generally cyclic in nature, which could considerably alter the recovery potential.

Boilers

For the eight boilers, stack temperatures ranged from a minimum of 425 K to 589 K. The waste heat content ranged from 10.2 percent to 51.0 percent. Five of the boilers were equipped with air preheaters, estimated to recover 8.2 to 14.5 percent of the fuel heat input. The recoverable energy for five of the boilers ranged from a minimum of 4.8 percent to a maximum of 17.6 percent by the process heat option. There were two sites where recoverable energy was less than 0.5 MW, which were not suitable for any recovery technique.

Internal Combustion Engines

The stack temperatures for the two internal combustion engines were 475 and 622 K. The waste heat content was 21.4 and 38.2 percent. The recoverable energy was less than 0.5 MW.

Gas Turbine Combined Cycle

Stack temperatures for the two units tested were 456 K and 499 K. The waste heat content was 15.3 and 16.1 percent. The recoverable energy by process heat was 2.1 and 3.3 percent of the fuel heat input, but due to the size of the units, the amount of energy recoverable is large.

POLLUTION CONTROL ENERGY

The objective of this portion of the program was to document the energy penalty of particulate emissions control, analyze the overall emissions effect when considering the power plant emissions generated to operate the

pollution control equipment, and compare energy requirements with the potential recoverable energy for the combustion device. The data generated from these analyses provide needed additional information on the operating penalties and benefits of particulate emissions control devices.

A summary of the results obtained is shown in Table 4. The ratio of emissions reduced at the plant to the emissions generated at the power plant, ranged from 7.3 for an emissions reduction of 148 kg/hr to 23,100 for an emissions reduction of 36,929 kg/hr with an average value for nine devices of 3,717. The power plant emissions are considerably less than the emissions reduction at the plant.

The energy consumed by the pollution control equipment ranged from 0.2 percent to 2 percent of industrial combustion unit heat input with an average value of 0.84 percent.

The ratio of recoverable energy to the pollution control energy ranged from 0 to 49. There were two sites that had no recoverable energy; at the seven other sites recoverable energy was considerably greater than energy required for pollution control.

CONCLUSIONS

The pollution emission and energy data cited in this report represent a small sample of industrial combustion equipment. The data are intended to present the general emission and energy characteristics of each type of equipment tested. Because of the small sample size, application of the data to estimate mean emissions from a class of similar equipment, or to predict emissions from any other single piece of equipment, or for use in establishing emissions standards would be a misapplication. The following conclusions are based on results of this limited study, but may represent general trends.

Waste Heat Content and Recoverable Energy

The following are the major conclusions on waste heat content of flue gas for the units tested:

- Metal processing furnaces require high temperatures and, in the absence of heat recovery, are highly inefficient with waste heat content ranging from 57 percent to 86 percent.
- Dry process mineral kilns are reasonably efficient with low waste heat content ranging from 11 percent to 13 percent.
- Stack gas waste heat content for industrial processes, as a percent of fuel heat input varies substantially, from a low of 10 percent up to 86 percent.
- Wet process cement kilns have high waste heat content (46 and 55 percent) primarily due to the high water vapor content of the flue gas.
- Refinery process heaters and boilers generally had moderate waste heat content in the 10-25 percent range with isolated cases having waste heat content in the 30-50 percent range;

TABLE 4. POLLUTION CONTROL ENERGY SUMMARY

Combustion Device	Location/ Unit - Test	Fuel*	Fuel Heat Input, MW	Pollution Control		Pollution Control Analysis	
				Equipment	Energy Required, %	(Emissions Reduced / Utility Emissions)	(Recoverable Energy / Pollution Control Energy)
Petroleum Process Heaters	4	Gas/Oil	30.9	None			
(Natural Draft)	4	RG*	31.1	None			
	5/1	RG	18.5	None			
	5/2	RG	10.1	None			
	7/1	RG	15.5	None			
	7/2	RG	15.1	None			
	7 (2645)	NG	15.9	None			
	7 (2645)	NG/No. 6	14.3	None			
(Forced Draft)	12/1-1	RG	22.5	None			
	12/1-8	RG/No. 6	22.5	None			
	12/2-1	RG	10.2	None			
	12/2-2	No.6	10.2	None			
Mineral Kilns							
Clay	1-1	NG	12.4	None			
Cement, dry process	3-2	Coke/NG	68.9	Multicyclone and Baghouse	1.2	6631	3.9
Cement, wet process	9-1A	NG	61.4		0.7	1348	2.0
Cement, wet process	9 (2645)	Coal	57.1	No Data			
Lime	6 (2645)	No. 6	15.6	No Data			
Metal Processing Furnaces							
Aluminum Melter	6-1	NG	6.5	None			
Aluminum Melter	6-3	No. 2	7.1	None			
Steel Open Hearth	14-1	NG/No. 6	30.3	ESP	2.0	7.3	--
Steel Reheat	16/1-17	NG	24.6	None			
Steel Soaking Pit	16/2-7	NG	2.3	None			

(continued)

*RG = Refinery Gas, NG = Natural Gas, Blk Liq. = Black Liquor, CO = Carbon Monoxide

TABLE 4. (CONTINUED)

Combustion Device	Location/ Unit - Test	Fuel	Fuel Heat Input, MW	Pollution Control		Pollution Control Analysis	
				Equipment	Energy Required, %	(Emissions Reduced / Utility Emissions)	(Recoverable Energy / Pollution Control Energy)
Boilers	10/1-1	Wood/NG	75.3	Multicylone and Venturi Scrubber	1.8	72	5.5
	10/2-2	Blk Liq.	140.3	ESP	0.2	1866	--
	13-6	Wood/Coal	25.5	Multicyclone	0.5	98.6	9.2
	11-1	CO/RG	94.9	Multicyclone	0.5	23,100	38.0
	19-53	No. 2	5.0	None			
	19-97	No. 6	5.8	None			
	19-181	NG	5.7	None			
	200-G-2	NG	11.7	None			
	200-24	No. 6	11.2	None			
	3 (2645)	Wood/Coal	29.4	Multicyclone	0.4	267	6.5
	5 (2645)	Wood/Oil	78.0	Multicyclone and Venturi Scrubber	0.3	68.6	49.0
Internal Combustion Engine	2-1	NG	3.2	None			
	15-1	No. 2	1.3	None			
Gas Turbine Combined Cycle	7/3-1	RG*	202	None			
	8-1	RG	519.9	None			

*RG = Refinery Gas, NG = Natural Gas, Blk Liq. = Black Liquor, CO = Carbon Monoxide

CO boiler (51 percent), wood bark boiler (39 percent), natural draft refinery heater (38 percent).

- Internal combustion engines showed significant waste heat content of 21 percent and 38 percent.
- Gas turbine combined cycles had low waste heat content of 15 percent and 16 percent.

The following conclusions were drawn with respect to the potential for energy recovery of stack gas waste heat using one or more of the three energy recovery techniques analyzed:

- Stack gas temperatures are sufficiently high (up to 1583 K) on many industrial devices to provide good potential for energy recovery.
- Some industrial devices have little potential for energy recovery due either to low stack gas temperatures or low gas flow rates.
- Where stack gas energy recovery appears feasible, the recoverable energy ranges from 1.4 to 76 percent of the fuel heat input, dependent on stack temperature and recovery method.
- Metal processing furnaces provide the best potential recoverable energy, ranging from 34 percent to 76 percent of fuel heat input.
- Internal combustion engines and gas turbine combined cycles appear to have the least potential for energy recovery.
- Recovery of waste heat by process hot water or steam appears to offer the highest potential for energy recovery.
- Combustion air preheat appears somewhat less favorable compared to process heat but is frequently employed because it does not require an external process in which to absorb the recovered energy. In several cases, e.g., petroleum process heaters, air preheat is only slightly less favorable than process heat.
- Thermodynamic heat engine cycles do not appear favorable compared to process heat or air preheat, but would be favored if energy recovered as electricity were the most desireable.

Pollution Control - Energy Requirements

The following conclusions are made with regard to the pollution control device effectiveness and energy requirements for the units examined:

- The emissions reduced at industrial plants are considerably greater than the emissions generated at power plants to operate the control equipment varying from a mass ratio of 7.3 for a low particulate reduction of 148 kg/hr to 23,100 for a high particulate reduction of 36,929 kg/hr.
- The recoverable energy at industrial plants was considerably greater than the energy requirement for pollution control in 7 of 9 cases by a ratio ranging from 2 to 49.

- The assessments of pollution control energy and emissions reduction were based on limited data, supplemented with estimates where necessary, introducing a higher degree of uncertainty compared with assessments of waste heat content.

Conclusions Regarding the Attainment of the Objectives of the Study

With regard to the primary program objective to determine the energy recovery potential and pollution control energy consumption of industrial combustion devices for which site-specific data had been gathered, the following conclusions were made:

- Based on test data gathered in field test programs to evaluate combustion modifications, it was possible to determine the waste heat content of the stack gases.
- Determinations of recoverable energy pollution control energy consumption and emission reductions were made largely from estimated performance, not from test data.

SECTION 3

RECOMMENDATIONS

As a result of this study, the following recommendations are made:

- Further investigation should be made into the application of waste heat recovery on metal processing furnaces as this has the greatest potential for energy efficiency improvement.
- Further investigation should be conducted of the use of process heat as an option for waste heat recovery as compared with combustion air preheating, with emphasis on the petroleum industry.
- The results of this study should be compared with other studies of industrial energy use to improve the assessment of nationwide potential for industrial energy recovery.
- The study of pollution control energy should be expanded to include SO_x removal equipment and additional sites with particulate removal.

SECTION 4

WASTE HEAT CONTENT AND RECOVERABLE ENERGY

This section presents the results and analysis of the waste heat content and recoverable energy for the devices included in this program. As the combustion devices tested had wide variations in flue gas temperatures and operating characteristics, the data are presented separately for each category of device.

PETROLEUM PROCESS HEATERS

Petroleum process heaters of natural-draft and forced-draft types were tested during Contracts 68-02-2144 and 68-02-2645. In total, fuel flow, exhaust composition and exhaust temperature measurements were taken on eight heaters of which two were forced draft units (Sites 12/1 and 12/2). In four cases (Sites 4, 12/1, 12/2, and 7 [2645]), the heaters were tested while firing refinery gas only; refinery gas and oil; or oil only. At the remaining sites (5/1, 5/2, 7/1, and 7/2) only refinery gas was fired. Table 5 presents the combustion and process data obtained on the process heaters.

The stack temperature for the natural draft petroleum process heaters ranged from 478 K to 780 K. The waste heat content ranged from 13.9 percent to a high of 38.4 percent.

The stack temperature for the forced draft heaters ranged from 546 K to 563 K. The waste heat content ranged from 16.0 percent to 35.3 percent.

There is no waste heat associated with the processed material (crude oil) itself. The function of the heaters is to heat the crude oil to the temperature required for further processing. There are options in the refinery process for process waste heat recovery. However, these options involve the entire refinery as an integrated complex. The scope of this program was restricted to the heaters themselves as separate entities, as this study did not provide the resources necessary for analyses of overall refinery heat balances.

The results of the process heater energy recovery analysis are shown in Table 6. The first four rows of data are extracted from Table 5 and 6 include the data pertinent to the recovery analysis.

One process heater, Site 12/1, Tests 12/1-1 and 12/1-8, is equipped with an air preheater. Data from analysis of this existing preheater (shown in parentheses in the table) indicates an effectiveness of about 0.60, with a heat recovery of about 12 to 13 percent of the fuel input heat. In analyzing the test data for this unit, the stack temperature was measured at 396 K (253°F). However, Table 6 indicates a recovery unit exit temperature of 606 K

TABLE 5. COMBUSTION AND PROCESS DATA, PETROLEUM PROCESS HEATERS

Unit Type		Natural Draft Process Heaters								Forced Draft Process Heaters			
Location/Unit - Test		4-4	4-6	5/1-1	5/2-1	7/1-1	7/2-1	7-2-2 (2645)	7-5-1 (2645)	12/1-1	12/1-8	12/2-1	12/2-2
Sampling Location		Common Duct	Common Duct	Heater Outlet Duct	Heater Outlet Duct	Heater Outlet Duct	Heater Outlet Duct	Heater Outlet Duct	Heater Outlet Duct	Duct	Duct	Stack	Stack
FUEL DATA													
Fuel Type		Ref. Gas/ Oil	Ref. Gas	Ref. Gas	Ref. Gas	Ref. Gas	Ref. Gas	NG	NG/ #6 Oil	Ref. Gas	Ref. Gas/ #6 Oil	Ref. Gas	#6 Oil
Flow - Gas	(m^3/s)	0.40	0.63	0.30	0.17	0.43	0.42	0.45	0.27	0.61	0.20	0.27	
- Liquid	(kg/s)	0.31											
- Solid	(kg/s)								0.10		0.35		0.24*
Heating Value - Gas	(MJ/m^3)	44.2	49.4	61.3	61.3	35.8	36.4	35.3	35.3	37.1	37.1	37.1	
- Liquid/Solid	(MJ/kg)	44.3											
Fuel Heat Input	(MW)	30.9	31.1	18.5	10.1	15.5	15.1	15.9	46.7 14.3	22.5	42.9 22.5	10.2	42.8 10.2*
COMBUSTION AIR DATA*													
Air Temperature	(K)	294	294	291	297	303	303	299	302	658 (291)*	658 (291)*	316	316
Percent Excess Air	(%)	20	22.5	24	20.5	53	62.5	22.1	13.6	9	17	23	24
Air Flow	(kg/s)	11.7	11.8	7.0	3.7	7.1	7.4	6.32	5.97	7.5	8.3	3.6	4.1
FLUE GAS COMPOSITION DATA (Mole Fraction, wet basis)													
Oxygen		0.0320	0.0340	0.0360	0.0350	0.0620	0.074	0.361	0.246	0.0150	0.0300	0.0300	0.0370
Nitrogen		0.6848	0.6928	0.6929	0.7609	0.6809	0.733	0.7438	0.7921	0.7295	0.7565	0.6058	0.7357
Carbon Dioxide		0.0950	0.0850	0.0830	0.0930	0.0620	0.061	0.0798	0.0787	0.0820	0.1150	0.0640	0.0990
Carbon Monoxide		--	0.0001	--	--	--	--	--	--	--	--	--	--
Water		0.1880	0.1860	0.1880	0.1110	0.1950	0.132	0.1403	0.1045	0.1730	0.0980	0.3000	0.1280
Sulfur Dioxide		0.000106	--	0.000006	0.000004	--	0.000005	--	--	0.000220	0.000340	0.000090	0.000280
Nitric Oxide		0.000069	0.000134	0.000075	0.000065	0.000060	0.000051	--	--	0.000319	0.000205	0.000130	0.000120
FLUE GAS DATA*													
Gas Temperature	(K)	550	557	478	481	592	780	693	687	606 (915)*	546 (876)*	563	556
Gas Flow	(kg/s)	14.17	12.54	7.62	3.8	7.66	7.7	6.62	6.25	7.94	8.97	4.38	4.40
Molecular Weight (Wet)	(kg/kg Mole)	27.77	27.58	27.59	28.52	27.29	27.95	28.02	28.31	27.66	29.00	26.15	28.47
Specific Heat	(kJ/kg-K)	1.13	1.17	1.13	1.09	1.13	1.13	1.13	1.13	1.13	1.04	1.17	1.13
Flue Gas Enthalphy (Ref. to 298 K)	(MJ/kg)	0.529	0.598	0.499	0.368	0.548	0.755	0.605	0.538	0.583	0.404	0.822	0.471
Percentage Waste Heat Content as Non-Condensible	(%)	42.7	45.3	34.2	45.7	57.1	72.5	65.4	28.8	19.3	33.0	33.3	57.1
Waste Heat Content	(MW)	7.5	7.5	3.8	1.4	4.2	5.8	4.00	3.36	4.6	3.6	3.6	2.1
Waste Heat Content as a Percent of Fuel Heat Input	(%)	24.3	24.1	20.5	13.9	27.1	38.4	25.2	23.5	20.4	16.0	35.3	20.6
Process Material Waste Heat		None	None	None	None	None	None	None	None	None	None	None	None

*For existing heat recovery device, combustion air and flue gas data are downstream of the device. Upstream temperatures are shown in parentheses.

TABLE 6. ENERGY RECOVERY ANALYSIS, PETROLEUM PROCESS HEATERS

Unit Type		Natural Draft Process Heaters								Forced Draft Process Heaters			
Location/Unit - Test		4-4	4-6	5/1-1	5/2-1	7/1-1	7/2-1	7-2-2 (2645)	7-5-1 (2645)	12/1-1	12/1-8	12/2-1	12/2-2
Fuel Heat Input	(MW)	30.9	31.1	18.5	10.1	15.5	15.1	15.9	14.3	22.5	22.5	10.2	10.2
Flue Gas Temperature	(K)	550	557	478	481	592	780	693	687	396 (915)	398 (876)	563	556
Waste Heat Content	(MW)	7.5	7.5	3.8	1.4	4.2	5.8	4.0	3.4	4.6	3.6	3.6	2.1
Waste Heat Content as a Percent of Fuel Heat Input	(%)	24.3	24.1	20.5	13.9	27.1	38.4	25.2	23.5	20.4	16.0	35.3	20.6
AIR PREHEAT OPTION													
Recovery Unit Exit Temp.	(K)	418	408	400	400	425	495	459	458	(606)	(546)	441	417
Effectiveness	(-)	0.7	0.7	0.5	0.5	0.7	0.7	0.7	0.7	(0.59)	(0.63)	0.7	0.7
Recoverable Energy	(MW)	2.1	2.2	0.7	<0.5	1.4	2.5	1.8	1.6	(2.8)	(3.1)	0.63	0.7
Recoverable Energy/Input	(%)	6.8	7.0	3.6	N/A	9.3	16.5	11.0	11.3	(12.3)	(13.7)	6.1	6.8
Cost	($1000)	360	362	265	N/A	238	235	242	227	E*	E*	185	185
Annual Savings	($1000)	287	297	91	N/A	196	338	238	220	E	E	85	150
PROCESS HEAT OPTION													
Recovery Unit Exit Temp.	(K)	400	400	400	400	400	400	400	400	400	400	400	400
Recoverable Energy	(MW)	2.4	2.3	0.67	<0.5	1.6	3.3	2.2	2.0	1.9	1.4	0.84	0.78
Recoverable Energy/Input	(%)	7.8	7.4	3.6	--	10.7	21.9	13.8	14.2	8.2	6.1	8.2	7.6
Cost	($1000)	187	182	81	N/A	145	236	176	166	156	127	93	89
Annual Savings	($1000)	327	313	91	N/A	226	450	298	276	251	185	114	168
HEAT ENGINE OPTION													
Recovery Unit Exit Temp.	(K)	416	416	N/A	N/A	416	416	416	416	416	416	416	416
Recoverable Energy	(MW)	<0.5	<0.5	--	--	<0.5	0.70	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Recoverable Energy/Input	(%)	--	--	--	--	--	4.6	--	--	--	--	--	--
Cost	($1000)	N/A	N/A	--	--	N/A	1394	N/A	N/A	N/A	N/A	N/A	N/A
Annual Savings	($1000)	N/A	N/A	--	--	N/A	446	N/A	N/A	N/A	N/A	N/A	N/A

* E = Existing, measured heat recovery device temperatures indicated in parentheses, when available.
N/A = Not applicable, temperatures too low or heat recovery <0.5 MW.

and 546 K for the two tests. These latter temperatures were derived from a heat balance of the preheater, assuming no leakage. The much lower stack temperature was measured at a point about 15 meters from the exit of the preheater. The discrepancy between this measurement and the derived exit temperature is attributed to heat loss from the 15-meter duct leading from the preheater exit up to the stack. Assuming that the derived preheater exit temperature is in fact correct, further heat recovery would be possible using the process heat option to reduce the temperature to 400 K. As shown in Table 6, this would recover an additional 1.4 to 1.9 MW of thermal energy.

The air preheat option was found to be applicable to most of the remaining heaters (those without existing preheat). The exceptions were Unit 5/2 for which the recoverable energy was less than 0.5 MW, and Units 5/1 and 12/2 with recoverable energy only marginally over 0.5 MW. The Location 5 units are connected together by a common convection section (i.e., existing process heat option) in the stack which generates steam, resulting in the lowest stack temperatures of units tested.

Estimates of recoverable energy by the air preheat option ranged from 0.63 MW to 2.5 MW. As a percent of fuel heat input, the estimated recoverable energy ranges from 6.1 to 16.5 percent.

Estimates of recoverable energy by the process heat option are slightly higher compared to the air preheat option. The installed cost is equal to or lower and the fuel savings are always higher compared with the air preheat option.

The heat engine option does not appear favorable for process heaters since estimates for all units, except 7/2-1 were less than 0.5 MW. Installed costs are over five times higher in this case, with no significant increase in fuel cost savings.

These estimates indicate that the process heat option would offer the most advantage for application to process heater waste heat recovery.

MINERAL KILNS

Energy measurements were made on five mineral kilns; three rotary cement kilns, a rotary lime kiln, and a clay tunnel kiln. Table 7 presents the combustion and process data. The flue gas energy flux ranged from 1.4 MW to 33.8 MW. The wet process cement kilns, Sites 9-1A and 9-(2645), have the highest waste heat content of all the devices examined in this program. Although these units are not the largest in terms of heat input, the waste heat content is high because of high moisture content, 43.6 and 34.8 percent. This high loss is in spite of the fact that stack temperatures are fairly low at 422 and 455 K for the two sites. It is of interest that waste heat content of 56 and 46 percent, respectively, relative to the fuel heat input, would be tolerated. The wet cement process is being phased out primarily because of poor efficiency. However, the process does have advantages in providing a more uniform feed mixture and is preferred by some cement companies for historical process knowledge reasons and due to characteristics

TABLE 7. COMBUSTION AND PROCESS DATA, MINERAL KILNS

Unit Type		Clay Tunnel Kiln	Dry Process Cement Kiln	Wet Process Cement Kiln	Wet Process Cement Kiln	Lime Kiln
Location/Unit - Test		1-1	3-2	9-1A	9-(2645)	6-(2645)
Sampling Location		Stack	Duct to Baghouse	Duct	Stack	Stack
FUEL DATA						
Fuel Type		Nat. Gas	Coke/Nat. Gas	Nat. Gas	Coal	No. 6 Oil
Flow - Gas	(m^3/s)	0.33	0.57	1.60	--	--
- Liquid	(kg/s)	--	--	--	--	--
- Solid	(kg/s)	--	1.45	--	2.0	0.39
Heating Value - Gas	(MJ/m^3)	38.8	39.7	38.3	--	--
- Liquid/Solid	(MJ/kg)	--	32.5	--	28.5	39.9
Fuel Heat Input	(MW)	12.4	69.9	61.4	57.1	15.6
COMBUSTION AIR DATA						
Air Temperature	(K)	305	672	672	1144	1402
Percent Excess Air	(%)	30	10.6	36	18	40.5
Air Flow	(kg/s)	5.0	24.9	25.8	33.9	9.36
FLUE GAS COMPOSITION DATA						
(Mole Fraction, wet basis)						
Oxygen		0.1650	0.0180	0.0340	0.019	0.046
Nitrogen		0.7709	0.7071	0.4385	0.407	0.447
Carbon Dioxide		0.0350	0.1500	0.0900	0.225	0.465
Carbon Monoxide		0.0020	--	--	--	--
Water		0.0270	0.1240	0.4360	0.348	0.042
Sulfur Dioxide		--	0.000012	--	--	--
Nitric Oxide		0.000015	0.000890	0.001500	--	--
FLUE GAS DATA						
Gas Temperature	(K)	330	558	422	455	527
Gas Flow	(kg/s)	18.67	19.52	36.83	35.9	9.75
Molecular Weight (Wet)	(kg/kg Mole)	28.95	25.22	25.22	28.26	35.2
Specific Heat	(kJ/kg-K)	1.00	1.04	1.09	1.09	1.1
Flue Gas Enthalphy (Ref. to 298 K)	(MJ/kg)	0.075	0.461	0.918	0.691	0.301
Percentage Waste Heat Content as Non-Condensible	(%)	38.6	52.2	13.3	29.3	83.4
Waste Heat Content	(MW)	1.4	9.0	33.8	24.8	2.9
Waste Heat Content as a Percent of Fuel Heat Input	(%)	11.3	12.9	55.1	45.7	18.8
Process Waste Heat		Nil	Nil	Nil	Nil	Nil

of the local composition of feed materials. In localities where the feed materials have a high moisture content as mined, it may be more efficient to use the wet process rather than expend energy to dry the feed for use in a dry process. Energy recovery on cement kilns, both wet and dry, is complicated by very high particulate loadings and by the fact that the particulate material contains alkali sulfates which have a tendency to promote plugging.

Process material waste heat is negligible in the kiln processes examined. To achieve the desired material properties, a controlled cooling is required and this is accomplished by preheating the combustion air by passing it through the product material as it leaves the kiln. This cooling reduces the process material below the 400 K temperature limit, taken as the lower practical limit in this study.

The preheating of combustion air by the product precludes the use of the air preheat option as a means of waste heat recovery for all the kilns examined, as shown in Table 8 for the air preheat option. The process heat option might be applicable to four of the kilns (the exception being the clay tunnel kiln) with from 0.9 to 3.2 MW potentially recoverable. The heat engine option does not appear favorable because of low temperatures (<533 K) and high installed cost.

In view of the relatively low stack temperatures and severe plugging tendency of the industrial categories studied, the mineral kilns appear to offer a low potential for waste heat recovery.

METAL PROCESSING FURNACES

The following four types of devices were field tested:

1. An aluminum melt furnace (Site 6)
2. A steel open hearth furnace (Site 14)
3. A steel reheat furnace (Site 16/1)
4. A steel soaking pit (Site 16/2)

Table 9 summarizes the combustion and process data for these metal processing furnaces.

Of all the devices tested, these devices had the highest flue gas temperatures ranging up to 1583 K. The range of fuel heat input was 2.3 to 30.3 MW and the waste heat content in flue gas relative to 298 K varied from 2.0 to 18.2 MW. The waste heat content as a percent of the fuel heat input varied from 60.0 to 86.3 percent.

Table 10 presents the energy recovery analysis results. The recoverable energy for the metal furnace flue gases ranged from 0.98 to 8.4 MW as discussed below.

No analysis of process material waste heat recovery was attempted. All the processes are batch type and the cooling rate of the materials may be

TABLE 8. ENERGY RECOVERY ANALYSIS, MINERAL KILNS

Unit Type		Clay Tunnel Kiln	Dry Process Cement Kiln	Wet Process Cement Kiln	Wet Process Cement Kiln	Lime Kiln
Location/Unit - Test		1-1	3-2	9-1A	9-(2645)	6-(2645)
Fuel Heat Input	(MW)	12.4	69.9	61.4	57.1	15.6
Flue Gas Temperature	(K)	330	558	422	494	527
Waste Heat Content	(MW)	1.4	9.0	33.8	26.1	2.9
Waste Heat Content as a Percent of Fuel Heat Input	(%)	11.3	12.9	55.1	45.7	18.8
AIR PREHEAT OPTION						
Recovery Unit Exit Temp.	(K)	E*	E*	E*	E*	E*
Effectiveness	(-)	N/A	N/A	N/A	N/A	N/A
Recoverable Energy	(MW)	--	--	--	--	--
Recoverable Energy/Input	(%)	--	--	--	--	--
Cost	($1000)	--	--	--	--	--
Annual Savings	($1000)	--	--	--	--	--
PROCESS HEAT OPTION						
Recovery Unit Exit Temp.	(K)	N/A	400	400	400	400
Recoverable Energy	(MW)	--	3.2	0.88	2.2	1.4
Recoverable Energy/Input	(%)	--	4.6	1.4	3.8	8.7
Cost	($1000)	--	231	96	174	127
Annual Savings	($1000)	--	436	120	172	294
HEAT ENGINE OPTION						
Recovery Unit Exit Temp.	(K)	N/A	416	N/A	N/A	N/A
Recoverable Energy	(MW)	--	0.63	--	--	--
Recoverable Energy/Input	(%)	--	0.91	--	--	--
Cost	($1000)	--	1268	--	--	--
Annual Savings	($1000)	--	406	--	--	--

* E = Existing, combustion air preheated in kiln product cooler
N/A = Not applicable, temperatures too low

TABLE 9. COMBUSTION AND PROCESS DATA, METAL PROCESSING FURNACES

Unit Type		Aluminum Melter		Steel Open Hearth	Steel Reheat	Steel Soaking Pit
Location/Unit - Test		6-1	6-3	14-1	16/1-17	16/2-1
Sampling Location		Stack	Stack	Duct to ESP	Stack	Duct
FUEL DATA						
Fuel Type		Nat. Gas	No. 2 Oil	Nat. Gas/ No. 6 Oil	Nat. Gas	Nat. Gas
Flow - Gas	(m^3/s)	0.17		0.66	0.63	
- Liquid	(kg/s)		0.16	0.37		0.06
- Solid	(kg/s)					
Heating Value - Gas	(MJ/m^3)	38.1		21.6	39.1	39.1
- Liquid/Solid	(MJ/kg)		45.2	43.2		
Fuel Heat Input	(MW)	6.5	7.1	30.3	24.6	2.3
COMBUSTION AIR DATA						
Air Temperature	(K)	311	303	1339	311	311
Percent Excess Air	(%)	25	50	243	17	45
Air Flow	(kg/s)	2.4	3.4	29.6	8.9	1.1
FLUE GAS COMPOSITION DATA (Mole Fraction, wet basis)						
Oxygen		0.0370	0.0650	0.1270	0.1330	0.0620
Nitrogen		0.6799	0.7288	0.6782	0.7530	0.7539
Carbon Dioxide		0.0870	0.1040	0.0410	0.0340	0.0700
Carbon Monoxide		--	--	--	--	--
Water		0.1960	0.1020	0.1530	0.0800	0.1140
Sulfur Dioxide		0.000003	0.000121	0.000020	--	--
Nitric Oxide		0.000082	0.000127	0.000800	0.000035	0.000070
FLUE GAS DATA						
Gas Temperature	(K)	1211	1208	550	730	1583
Gas Flow	(kg/s)	2.73	3.61	34.79	23.47	1.10
Molecular Weight (Wet)	(kg/kg Mole)	27.58	28.91	27.65	28.28	28.23
Specific Heat	(kJ/kg-K)	1.25	1.17	1.13	1.09	1.34
Flue Gas Enthalpy (Ref. to 298 K)	(MJ/kg)	1.428	1.191	0.523	0.597	1.818
Percentage Waste Heat Content as Non-Condensible	(%)	76.9	88.4	52.7	76.4	90.0
Waste Heat Content	(MW)	3.9	4.3	18.2	14.0	2.0
Waste Heat Content as a Percent of Fuel Heat Input	(%)	60.6	61.5	60.0	56.8	86.3
Process Material Waste Heat		N/A	N/A	N/A	N/A	N/A

TABLE 10. ENERGY RECOVERY ANALYSIS, METAL PROCESSING FURNACES

Unit Type		Aluminum Melter		Steel Open Hearth	Steel Reheat	Steel Soaking Pit
Location/Unit - Test		6-1	6-3	14-1	16/1-17	16/2-1
Fuel Heat Input	(MW)	6.5	7.1	30.3	24.6	2.3
Flue Gas Temperature	(K)	1211	1208	550	730	1583
Waste Heat Content	(MW)	3.9	4.3	18.2	14.0	2.0
Waste Heat Content as a Percent of Fuel Heat Input	(%)	60.6	61.5	60.0	56.8	86.3
AIR PREHEAT OPTION						
Recovery Unit Exit Temp.	(K)	766	695	E*	720	915
Effectiveness	(-)	0.7	0.7	N/A	0.7	0.7
Recoverable Energy	(MW)	1.5	2.2	--	2.6	0.98
Recoverable Energy/Input	(%)	23.4	30.5	--	10.7	42.8
Cost	($1000)	141	149	--	314	76
Annual Savings	($1000)	207	468	--	357	134
PROCESS HEAT OPTION						
Recovery Unit Exit Temp.	(K)	400	400	N/A	400	400
Recoverable Energy	(MW)	2.8	3.4	--	8.4	1.7
Recoverable Energy/Input	(%)	42.6	48.1	--	34.3	75.8
Cost	($1000)	207	241	--	484	150
Annual Savings	($1000)	376	737	--	1148	237
HEAT ENGINE OPTION						
Recovery Unit Exit Temp.	(K)	416	416	N/A	416	N/A
Recoverable Energy	(MW)	0.60	0.74	--	1.8	<0.5
Recoverable Energy/Input	(%)	9.2	10.4	--	7.2	--
Cost	($1000)	1194	1472	--	3534	--
Annual Savings	($1000)	382	471	--	1131	--

*E = Existing

critical to metal properties. Assessment of heat recovery without detailed metallurgical information would be inappropriate.

The steel open hearth furnace, Site 14, is equipped with an exhaust gas heat recovery device to preheat combustion air. The recovery is accomplished with regenerative checker brick at each end of the furnace. Air flow and fuel flow are alternated between the two ends of the furnace. While firing at one end, exhaust gases exit at the opposite end, preheating the checker bricks. After about 15 minutes, fuel flow is cut off, flows are reversed, and firing is initiated at the opposite end, with combustion air picking up heat from the bricks that were heated during the previous cycle. Since this regenerative process differs from the conventional continuous flow gas-to-air heat exchanger, no attempt was made to analyze the thermal performance of this device as a calibration for the air preheat option. Table 10 indicates that none of the heat recovery options are applicable to the steel open hearth furnace. Although the stack temperature was measured at 550 K, this plant was equipped with a waste heat boiler system with one boiler serving several open hearth furnaces. Since measurements were made on only one furnace, it was not possible to conduct a heat balance and energy recovery analysis of the entire plant system.

The aluminum melter, Site 6, was found to have very high stack temperatures at about 1200 K, and offers excellent potential for energy recovery. With the air preheat option, the estimated recoverable energy firing gas fuel was 1.5 MW and firing oil fuel was 2.2 MW. The recoverable energy while firing oil is higher because the melter required higher excess air, 50 percent compared with 25 percent firing gas. With the air preheat option, the limitation of practical air preheater effectiveness to 0.7 results in relatively high recovery unit exit temperatures of 766 and 695 K as shown in Table 10. Use of the process heat option allows a much lower recovery unit exit temperature and increases the recoverable energy to 2.8 and 3.4 MW for gas and oil fuel, respectively. The installed cost is greater but annual fuel savings are higher. The heat engine option is far more costly to install and recovers far less energy compared with the other options. While the process heat option appears most favorable, there was no obvious method for use of hot water or steam in the aluminum plant. Therefore, the air preheat option may be the most practical for the aluminum melter.

In the Site 16 steel plant, the steel soaking pit, unit 16/2, had the highest stack temperature of all the devices tested, 1583 K, with an 86.3 percent waste heat content relative to fuel heat input. The steel reheat furnace, unit 16/1, had a lower stack temperature, 730 K, but a higher recoverable energy due to the higher fuel heat input compared with the soaking pit. The very poor fuel efficiencies on these steel furnaces reflect the poor economic state of the U.S. steel industry. This plant has been shut down since the tests reported here were conducted.

For the steel reheat furnace, the air preheat option would recover an estimated 2.6 MW, only 10.7 percent of the fuel heat input. The process heat option offers a greater recoverable energy of 8.4 MW, or 34.3 percent of the fuel input. The installed cost of the process heat option is estimated to be

54 percent greater than the air preheat option but the annual savings is three times that of the air preheat option. The heat engine option offers a potential 1.8 MW recovery with fuel savings about equal to the process heat option, but with significantly higher installed cost. It appears that the process heat option would be preferred for the steel reheat furnace.

Recoverable energy with the air preheat option applied to the steel soaking pit was 0.98 MW. The very high stack temperature, 1583 K, on this unit and a limit of 0.7 for exchanger effectiveness results in a recovery unit exit temperature of 915 K, well above the practical level of 400 K. At these high temperatures, the materials required for the air preheater would significantly increase the cost, a fact not reflected in the installed cost estimate. The process heat option provides an estimated 1.7 MW recoverable energy or 76 percent of the fuel heat input. Although temperatures are favorable for the heat engine option, the recoverable energy is below the practical level that would provide the required 0.5 MW minimum electrical power and this option is not applicable to the steel soaking pit. The process heat option appears the most favorable of the three.

BOILERS

The following seven boilers were field tested:

1. Three wood-bark boilers (Sites 10/1, 13, 3 [2645] and 5 [2645]) (Site 13 and 3 [2645] were the same boiler)
2. A black liquor recovery boiler (Site 10/2)
3. A CO boiler (Site 11)
4. Two industrial boilers (Sites 19 and 200)

Table 11 summarizes the combustion and process data for these boilers. The fuel heat input ranged from 5.0 to 140.3 MW while the measured flue gas temperatures varied from 478 to 589 K. The waste heat content varied from 0.9 to 48.4 MW. The variation of the waste heat content as a percent of the fuel heat input ranged from 10.2 to 51.0 percent.

Five of the boilers were equipped with air preheaters. Table 12 includes the results of the analysis of these preheaters. The effectiveness ranged from a low of 0.38 at Site 200 to 0.79 at Site 10/1. Excluding Site 38, a small boiler, the effectiveness averaged 0.73, supporting the assumption of 0.7 used in the recovery analysis of other units. In the analysis of the existing preheaters, on two of the boilers, Sites 10/1 and 13-6 (3-1 [2645]), it was not possible to obtain an energy balance based on the measured temperatures and flow rates of air and flue gas. The measured differentials for the air temperature increase were much higher than the corresponding gas temperature decrease. This indicates either leakage inside the preheater or bypass of air around the preheater, reducing the flow rate on the air side and increasing the air temperature rise. Use of air preheater bypass is common in boilers as a means of temperature control. Table 13 shows the measured temperature differentials and an apparent air bypass factor that would be necessary to explain the measured temperatures. The apparent air bypass factor is simply a correction factor by which the combustion air flow rate

TABLE 11. COMBUSTION AND PROCESS DATA, BOILERS

Unit Type		Wood	Black Liquor	Wood	CO Gas Fired	Oil and Gas Fired					Wood Fired	
Location/Unit - Test		10/1-1	10/2-2	13-6	11-1	19-53	19-97	19-101	2006-2	200-24	3-1 (2645)	5-1-1 (2645)
Sampling Location		Duct	Duct	Duct to Stack	Duct	Stack	Stack	Stack	Stack	Stack		
FUEL DATA												
Fuel Type		Wood-Bark & Nat. Gas	Black Liquor	Wood-Bark & Coal	CO Gas & Ref. Gas	No. 2 Oil	No. 6 Oil	Nat. Gas	Nat. Gas	No. 6 Oil	31% Wood 69% Coal	75% Wood 25% Oil
Flow - Gas	(m^3/s)	0.79	1.47		31.3(comb)			0.15	0.31			
- Liquid	(kg/s)					0.11	0.13			0.26		1.11
- Solid	(kg/s)	4.46		1.03(comb)							1.14	3.32
Heating Value - Gas	(MJ/m^3)	38.3			3.0(comb)			37.9	37.4			
- Liquid/Solid	(MJ/kg)	10.1	9.6	24.9(comb)		45.3	43.7			42.8	25.73	25.65
Fuel Heat Input	(MW)	75.3	140.3	25.5	94.9	5.0	5.8	5.7	11.7	11.2	29.4	78.0
COMBUSTION AIR DATA†												
Air Temperature	(K)	578 (317)†	394 (302)	486 (291)	311	294	294	294	412 (288)	416 (294)	489 (303)	555 (338)
Percent Excess Air	(%)	83	23	67	23	17	16	16	7	15	75.9	63.53
Air Flow	(kg/s)	41.7	46	13.8	31.3	1.8	2.2	1.6	3.9	4.1	12.98	30.78
FLUE GAS COMPOSITION DATA (Mole Fraction, wet basis)												
Oxygen		0.0780	0.0280	0.0750	0.0160	0.0260	0.0270	0.0250	0.0150	0.0270	0.093	0.0741
Nitrogen		0.6401	0.6031	0.7070	0.6881	0.6799	0.7525	0.6699	0.8138	0.7658	0.7140	0.7044
Carbon Dioxide		0.0630	0.1060	0.0950	0.1110	0.1050	0.1230	0.0860	0.0970	0.1270	0.105	0.1134
Carbon Monoxide		0.0008	0.0015	--	--	--	--	--	--	--	0.000362	0.0009
Water		0.2180	0.2610	0.1220	0.1840	0.1890	0.0970	0.2190	0.0740	0.0790	0.0868	0.1070
Sulfur Dioxide		--	0.000340	0.000820	0.000760	0.000060	0.000300	--	0.000944	0.000760	0.000667	0.00002
Nitric Oxide		0.000090	0.000020	0.000205	0.000133*	0.000090	0.000195	0.000073	0.000288*	0.000133*	0.00021	0.00006
FLUE GAS DATA†												
Gas Temperature	(K)	533 (648)†	425 (683)	478 (550)	589	543	527	538	496 (617)	491 (616)	489 (569)	513 (664)
Gas Flow	(kg/s)	49.92	57.58	15.17	78.28	2.03	2.27	1.77	3.81	4.35	14.89	38.92
Molecular Weight (Wet)	(kg/kg Mole)	27.14	27.21	28.63	28.03	27.90	29.12	27.29	28.87	29.39	29.2	29.05
Specific Heat	(kJ/kg-K)	1.13	1.17	1.04	1.13	1.09	1.09	1.17	1.04	1.04	1.123	1.106
Flue Gas Enthalphy (Ref. to 298 K)	(MJ/kg)	0.617	0.571	0.376	0.618	0.591	0.388	0.621	0.316	0.322	0.338	0.391
Percentage Waste Heat Content as Non-Condensible	(%)	33.1	39.7	47.4	52.5	42.5	56.7	39.1	53.3	55.7	63.4	60.8
Waste Heat Content	(MW)	30.8	32.9	5.7	48.4	1.2	0.88	1.1	1.2	1.4	5.03	15.2
Waste Heat Content as a Percent of Fuel Heat Input	(%)	40.9	23.4	22.4	51.0	23.5	15.1	24.8	10.2	12.9	17.1	19.5
Process Material Waste Heat		None	None	None	None	None	None	None	None	None	None	None

(comb) - two fuels combined average value

*NO_x readings on a cold dry basis

†For existing heat recovery device, combustion air and flue gas data are downstream of the device. Upstream temperatures are shown in parentheses, when available.

TABLE 12. ENERGY RECOVERY ANALYSIS, BOILERS

Unit Type		Wood	Black Liquor	Wood	CO Gas Fired	Oil and Gas Fired					Wood Fired	
Location/Unit - Test		10/1-1	10/2-2	13-6	11-1	19-53	19-97	19-101	200G-2	200-24	3-1 (2645)	5-1-1 (2645)
Fuel Heat Input	(MW)	75.3	140.3	25.5	94.9	5.0	5.8	5.7	11.7	11.2	29.4	78.0
Flue Gas Temperature	(K)	533	425	478	589	543	527	537	496	491	489	513
Waste Heat Content	(MW)	30.8	32.9	5.7	48.4	1.2	0.88	1.1	1.2	1.4	5.03	15.2
Waste Heat Content as a Percent of Fuel Heat Input	(%)	40.9	23.4	22.4	51.0	23.5	15.1	24.8	10.2	12.9	17.1	19.5
AIR PREHEAT OPTION												
Recovery Unit Exit Temp.	(K)	(533)	E*	(478)	506	N/A	N/A	N/A	(496)	(491)	(489)	(513)
Effectiveness	(-)	(0.79)	--	(0.75)	0.7	--	--	--	(0.38)	(0.38)	(0.7)	(0.67)
Recoverable Energy	(MW)	(10.9)	--	(2.7)	6.1	<0.5	<0.5	<0.5	(0.49)	(0.50)	(2.4)	(6.5)
Recoverable Energy/Input	(%)	(14.5)	--	(10.6)	6.5	--	--	--	(4.2)	(4.5)	(8.2)	(8.3)
Cost	($1000)	E*	--	E*	707	--	--	--	E*	E*	E*	E*
Annual Savings	($1000)	E*	--	E*	833	--	--	--	E	E	E	E
PROCESS HEAT OPTION												
Recovery Unit Exit Temp.	(K)	400	N/A	400	400	N/A	N/A	N/A	N/A	N/A	400	400
Recoverable Energy	(MW)	7.5	--	1.2	16.7	<0.5	<0.5	<0.5	<0.5	<0.5	1.5	4.9
Recoverable Energy/Input	(%)	10.0	--	4.8	17.6	--	--	--	--	--	5.0	6.2
Cost	($1000)	440	--	119	850	--	--	--	--	--	135	314
Annual Savings	($1000)	1019	--	98	2274	--	--	--	--	--	119	1048
HEAT ENGINE OPTION												
Recovery Unit Exit Temp.	(K)	N/A	N/A	N/A	416	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Recoverable Energy	(MW)	--	--	--	3.4	<0.5	--	<0.5	--	--	--	--
Recoverable Energy/Input	(%)	--	--	--	3.6	--	--	--	--	--	--	--
Cost	($1000)	--	--	--	6733	--	--	--	--	--	--	--
Annual Savings	($1000)	--	--	--	2155	--	--	--	--	--	--	--

* E = Existing, measured heat recovery device data is indicated in parentheses, when available.
N/A = Not applicable, temperature too low, or recovered energy <0.5 MW as indicated.

TABLE 13. ANALYSIS OF EXISTING BOILER AIR PREHEATERS

Unit Type Location/Unit - Test	Wood 10/1-1	Wood* 13-6	Gas 38-200G-2	Oil 38-200-24	Wood* 3-1 (2645)	Wood 5-1-1 (2645)
Air Inlet Temp., K	317	291	288	294	303	338
Air Outlet Temp., K	578	486	412	416	489	555
Gas Inlet Temp., K	648	550	617	616	569	664
Gas Outlet Temp., K	533	478	496	491	489	513
Air Temp. Increase, K	261	195	124	122	186	218
Gas Temp. Decrease, K	115	72	121	125	80	152
Apparent Air Bypass Factor	0.59	0.42	0.99	1.12	0.55	0.97

*Same boiler, different test periods

must be multiplied to obtain a gas-to-air heat balance based on the measured temperatures. This assumes, of course, that the temperatures are correct, neglecting the possibility of measurement errors. For Site 10/1 the air bypass factor was 0.59 and for Site 13-6 it was 0.42 while for a later test period on this same boiler it was 0.55 (3-1 [2645]). For Site 200 the factors were 0.99 for gas fuel and 1.12 for oil fuel, and at Site 5 it was 0.97. These values indicate no bypass. With the assumed apparent conditions, the recoverable energy for existing air preheaters ranges from 0.49 to 10.9 MW or 4.2 to 14.5 percent of the fuel heat input. Site 10/2-2 was not included in this analysis since the air preheater was a steam-air heater not involving exhaust gas recovery.

The boiler at Site 11 appeared amenable to installation of an air preheater with recoverable energy of 6.1 MW or 6.5 percent of the fuel heat input. For Site 19, none of the three heat recovery options appeared practical because the small size of the unit resulted in all recoverable energy values of less than 0.5 MW.

Assessment of the process heat and heat engine options were made considering these options as add-on options to the existing air preheaters. The process heat recovery option appeared applicable to Sites 10/1, 13-6, 11-1, 3-1 [2645], and 5-1-1 [2645]. Recoverable energy ranged from 1.2 to 16.7 MW, or 4.8 to 17.6 percent of the fuel heat input.

The heat engine option appeared applicable only to Site 11-1, the one unit with no air preheater for which the recoverable energy exceeded 0.5 MW. For all other units, the available temperature was less than the 533 K required for the heat engine option.

Based on this assessment, the process heat option appears favorable for application to industrial boilers as an enhancement of existing air preheaters. For Site 11, the one larger size boiler with no preheater, the process heat option appears more favorable than the air preheat option based on recovered energy and fuel savings.

INTERNAL COMBUSTION ENGINES

A natural gas engine (Site 2) and a diesel engine (Site 15) were field tested. The natural gas engine had a fuel heat input of 3.2 MW and the flue gas temperature was measured at 622 K. The waste heat content was 38.2 percent of the fuel heat input.

For the diesel engine, the fuel heat input was 1.3 MW with a flue gas temperature of 475 K and waste heat content of 21.4 percent.

Table 14 presents a summary of measurements and calculations for these engines. The results of the energy recovery analysis are also shown on Table 14. The air preheater option is not applicable and the process heat and heat engine criteria were not satisfied.

TABLE 14. COMBUSTION AND PROCESS DATA, INTERNAL COMBUSTION ENGINES

Location/Unit - Test		2-1	15-1
Sampling Location		Stack	Stack
FUEL DATA			
Fuel Type		Nat. Gas	Nat. Gas
Flow - Gas	(m^3/s)	0.071	
- Liquid	(kg/s)		0.027
- Solid	(kg/s)		
Heating Value - Gas	(MJ/m^3)	45.6	
- Liquid/Solid	(MJ/kg)		45.2
Fuel Heat Input	(MW)	3.2	1.3
COMBUSTION AIR DATA			
Air Temperature	(K)	300	289
Percent Excess Air	(%)	13	95
Air Flow	(kg/s)	1.1	0.8
FLUE GAS COMPOSITION DATA (Mole Fraction, wet basis)			
Oxygen		0.1150	0.0960
Nitrogen		0.7348	0.7479
Carbon Dioxide		0.0540	0.0720
Carbon Monoxide		0.0004	0.0001
Water		0.0950	0.0830
Sulfur Dioxide		--	0.000065
Nitric Oxide		0.000790	0.000975
FLUE GAS DATA			
Gas Temperature	(K)	622	475
Gas Flow	(kg/s)	2.46	0.81
Molecular Weight (Wet)	(kg/kg Mole)	28.39	28.76
Specific Heat	(kJ/kg-K)	1.09	1.17
Flue Gas Enthalphy (Ref. to 298 K)	(MJ/kg)	0.488	0.333
Percentage Waste Heat Content as Non-Condensible	(%)	68.3	55.6
Waste Heat Content	(MW)	1.2	0.27
Waste Heat Content as a Percent of Fuel Heat Input	(%)	38.2	21.4
Process Material Waste Heat		None	None
ENERGY RECOVERY ANALYSIS			
Air Preheat Option		N/A	N/A
Process Heat Option			
Recoverable Energy at 400 K	MW	<0.5 MW	<0.5 MW
Heat Engine Option			
Recoverable Energy at 415 K		<0.5 MW	(T <533 K)

GAS TURBINE COMBINED CYCLES

Two gas turbine combined-cycle systems were tested (Sites 7/3 and 8). In this system, a gas turbine supplies the combustion air to a boiler. Table 15 shows the summary of combined-cycle data. In one system, the combined fuel heat input to turbine and boiler was 202 MW; for the other system fuel heat input was 519.9 MW. The temperature of the flue gas leaving the boiler was 456 K for the smaller unit and 499 K for the larger unit.

Table 16 shows the energy recovery analysis results. The air preheat option is not applicable because the gas turbine inlet air must be near ambient temperature to avoid overheating the compressor. The heat engine option is not applicable because stack temperatures are below 533 K. The process heat option would recover 4.3 and 17.4 MW from the two systems, 2.1 and 3.3 percent of the fuel heat input.

TABLE 15. COMBUSTION AND PROCESS DATA,
GAS TURBINE COMBINED CYCLES

Location/Unit - Test		7/3-1	8-1
Sampling Location		Stack	Stack
FUEL DATA			
Fuel Type		Ref. Gas	Ref. Gas
Flow - Gas	(m^3/s)	5.69(comb)	15.34(comb)
- Liquid	(kg/s)		
- Solid	(kg/s)		
Heating Value - Gas	(MJ/m^3)	35.5	33.9
- Liquid/Solid	(MJ/kg)		
Fuel Heat Input	(MW)	202.0(comb)	519.9(comb)
COMBUSTION AIR DATA			
Air Temperature	(K)	658	697
Percent Excess Air	(%)	14*	10*
Air Flow	(kg/s)	~70.94†	~167.4†
FLUE GAS COMPOSITION DATA (Mole Fraction, wet basis)			
Oxygen		0.0490	0.0170
Nitrogen		0.7059	0.6979
Carbon Dioxide		0.0700	0.0750
Carbon Monoxide		--	--
Water		0.1750	0.2100
Sulfur Dioxide		--	--
Nitric Oxide		0.000078	0.000111§
FLUE GAS DATA			
Gas Temperature	(K)	456	499
Gas Flow	(kg/s)	68.15	150.3
Molecular Weight (Wet)	(kg/kg Mole)	27.57	27.17
Specific Heat	(kJ/kg-K)	1.13	1.17
Flue Gas Enthalphy (Ref. to 298 K)	(MJ/kg)	0.453	0.557
Percentage Waste Heat Content as Non-Condensible	(%)	34.0	37.3
Waste Heat Content	(MW)	30.9	83.7
Waste Heat Content as a Percent of Fuel Heat Input	(%)	15.3	16.1
Process Material Waste Heat		None	None

*On pure air basis
†Exhaust from gas turbine
§NO_x measurement cold dry basis only
comb = total for turbine and boiler

TABLE 16. ENERGY RECOVERY ANALYSIS,
GAS TURBINE COMBINED CYCLES

Location/Unit - Test		7/3-1	8-1
Fuel Heat Input	(MW)	202.0	519.9
Flue Gas Temperature	(K)	456	499
Waste Heat Content	(MW)	30.9	83.7
Waste Heat Content as Percent of Fuel Heat Input	(%)	15.3	16.1
AIR PREHEAT OPTION		N/A	N/A
PROCESS HEAT OPTION			
Recovery Unit Exit Temp.	(K)	400	400
Recoverable Energy	(MW)	4.3	17.4
Recoverable Energy/Input	(%)	2.1	3.3
Cost	($1000)	286	879
Annual Savings	($1000)	585	2366
HEAT ENGINE OPTION		N/A (T <533 K)	N/A (T <533 K)

SECTION 5

POLLUTION CONTROL ENERGY

OBJECTIVES AND SUMMARY

This section describes the energy analysis of nine particulate control devices tested under contracts 68-02-2144 and 68-02-2645. The direct inplant energy requirements were determined, particulate reduction estimated and these operating parameters were used to evaluate the following:

- Ratio of emissions reduced at the plant to emissions generated at an electric utility supplying power for the pollution control equipment.
- Ratio of recoverable energy to the pollution control energy.

The objectives of this portion of the program were to document the energy requirements of particulate emission controls, analyze the overall emissions effect when considering the electric utility emissions generated to supply power for the pollution control equipment, and compare energy requirements with the recoverable energy from the combustion device exhaust gas. The data generated from these analyses provide needed additional information on the operating penalties and benefits of particulate emissions control devices.

A summary of the results obtained is shown in Table 17. The ratio of emissions reduced at the industrial facility to the emissions generated at the electric utility, ranged from 7.3 for an emissions reduction of 148 kg/hr to 23,100 for an emissions reduction of 36,929 kg/hr. The electric utility emissions attributed to the pollution control devices are considerably less than the emissions reduction at the facility.

The ratio of recoverable energy to the pollution control energy ranged from 0 to 49. There were two sites that had no recoverable energy and at the seven other sites the recoverable energy was considerably greater than pollution control energy.

POLLUTION CONTROL DEVICE DESIGN INFORMATION

Each pollution control device was inspected to determine pertinent design information. Table 18 lists the control device type, manufacturer, serial number, and remarks regarding design operating information.

CALCULATION PROCEDURES

Energy Requirements

The energy required for pollution control was calculated as

Energy Requirement = Direct Energy + Indirect Energy

TABLE 17. POLLUTION CONTROL ENERGY SUMMARY

Site No.	Combustion Device	Pollution Control Device	Particulate Emissions Reduced kg/hr	(lb/hr)	Energy for Control, MW	Utility Fuel Heat Input MW (10^6 Btu/hr)		Utility Emissions kg/hr	(lb/hr)	Emission Reduced / Utility Emissions	Recoverable Energy MW	Recoverable Energy / Energy for Control
3	Cement Kiln (Dry)	Multicyclone & Baghouse	24,537	(53,982)	0.82	2.6	(8.9)	3.7	(8.1)	6,631	3.2	3.9
9-1A	Cement Kiln (Wet)	Electrostatic Precipitator	2,157	(4,746)	0.45	1.4	(4.8)	1.6	(3.5)	1,348	0.88	2.0
10/1	Wood/Bark Boiler	Multicyclone & Venturi Scrubber	354	(778)	1.36	4.3	(14.7)	4.9	(10.7)	72	7.5	5.5
10/2	Black Liquor Recovery Boiler	Electrostatic Precipitator	1,866	(4,105)	0.29	0.9	(3.1)	1	(2.3)	1,866	N/A	--
11	CO Boiler	Multicyclone	36,929	(81,243)	0.44	1.4	(4.8)	1.6	(3.5)	23,100	16.7	38
13	Wood/Bark Boiler	Multicyclone	562	(1,236)	0.13	0.5	(1.7)	5.7	(12.5)	98.6	1.2	9.2
14	Open Hearth Furnace	Electrostatic Precipitator	148	(326)	0.61	1.8	(6.1)	20.3	(44.7)	7.3	N/A	--
3 (2645)	Wood/Bark Boiler	Multicyclone	320	(704)	0.23	0.1	(0.35)	1.2	(2.6)	267	1.5	6.5
5 (2645)	Wood/Bark Boiler	Multicyclone & Venturi Scrubber	336	(741)	0.10	0.43	(1.5)	4.9	(10.7)	68.6	4.9	49

TABLE 18. POLLUTION CONTROL EQUIPMENT NAME-PLATE INFORMATION

Site	Combustion Device	Pollution Control Device	Manufacturer	Serial Number or Type	Remarks
3	Rotary Cement Kiln (Dry Process)	Multiclone	Western Precipitation Joy Manufacturing	Size 40-5 Type 24-1H	Design Pressure Drop = 10 cm Wg; Design Max. Temperature = 398.9 °C Gross Mass Design Efficiency = 80%; Number of Tubes = 40
		Baghouse	Dracco, Fuller Co.		Design Volume Flow Rate = 79.5 dNm^3/s; Design Pressure Drop = 14.2 cmWg; Design Temperature = 315.5 °C; Gross Mass Design Efficiency = 99.8%; Design Air/Cloth Ratio = 1.98; Number of Compartments = 28; Bag Composition = Silicon Glass; Bag Length = 7.8 m
9-1A	Rotary Cement Kiln (Wet Process)	Electrostatic Precipitator	Western Precipitation Joy Manufacturing	RSP	Design Volume Flow Rate = 44.09 dNm^3/s; Design Pressure Drop = 14 cmWg; Gross Mass Design Efficiency = 99.6%; Total Energy Consumption Rate = 275 kW; Number of Sections = 3; Design Voltage = 440V; Design Temperature = 288 °C; Number of Wires = 1944
10/1	Wood-Bark Boiler	Multiclone	Western Precipitation Joy Manufacturing	9VGR-AE 234-13	Design Volume Flow Rate = 49.4 dNm^3/s; Design Pressure Drop = 7.8 cmWg; Design Temperature = 240.5 °C
		Venturi Scrubbers	Zurn Industries		Design Volume Flow Rate = 43.1 dNm^3/s; Design Pressure Drop = 35.6 cm Wg; Design Temperature = 315.6 °C; Gross Mass Design Efficiency = 98.2%
13	Wood-Bark Boiler	Multiclone	Western Precipitation Joy Manufacturing	9VGR14 P-75248-B Serial 4.588	Design Volume Flow Rate = 18.45 dNm^3/s; Design Temperature = 236.7 °C; Design Pressure Drop = 6.1 cmWg; Total Energy Consumption Rate = 133 kW (509.7 K)

TABLE 18. (CONTINUED)

Site	Combustion Device	Pollution Control Device	Manufacturer	Serial Number or Type	Remarks
10/2	Black Liquor Recovery Boiler	Electrostatic Precipitator	Modified-Environmental Element & Research-Cottrell		Design Volume Flow Rate = 103.6 dNm^3/s; Design Temperature = 163 °C; Total Energy Consumption Rate = 264 kW; Gross Mass Design Efficiency = 99.6%
11	Carbon Monoxide (CO) Boiler	Multiclone	Ducon Corp.		7 sets of 3 stages: Stage 1 VM/700/150 Size 530 1.6 m OD; Stage 2 M/810/70 Size 410 1.5 m OD; Stage 3 810/40
14	Open Hearth Furnace	Electrostatic Precipitator	Western Precipitation Joy Manufacturing		Design Volume Flow Rate = 334.9 dNm^3/s; Design Pressure Drop = 12.7 cmWg; Design Temperature = 399 °C; Gross Design Efficiency = 99%; Total Energy Consumption Rate = 393.4 kW; Design Applied Voltage = 50000 volts; Number of Sections = 10; Plate Area = 48159 m^2
3 (2645)	Wood-Bark Boiler	Multicyclone	Western Precipitation Joy Manufacturing	9VGR14 P-75248-B Serial 4508	Design Volume Flow Rate = 18.45 dNm^3/s; Design Pressure Drop = 6.1 cmWg; Design Temperature = 235.7°C
9 (2645)	Hogged Fuel/ Oil Boiler	Multiclone	Universal Oil Products Co.; Air Correction Division	DES 6 UPSWHS 22-660	Design Parameters: Dust Sp. Gr. = 2.5; Dust Concentration = 2-5 gr/ft^3 (0.0046-0.0114 mg/cc); Gas Temperature = 70-800°F (294-700 K)
		Scrubber	Western Precipitation Joy Manufacturing	BSS Size 1100/ 2-80	Constant 15-in. H_2O ΔP; Variable Venturi; Dust Concentration = 0.25-0.4 gr/SDCF (0.00057-0.00092 mg/cc); 10% minimum; Water Flow Rate = 1600-1800 gal/min (6056-6813 lit/min); Water Temperature In = 60°F (289 K); Water Temperature Out = 135°F (331 K)

The direct energy was calculated from

Direct Energy = (device pressure drop) x (flue gas flow rate)

The indirect energy was calculated as follows

Indirect Energy = Energy for Peripheral Equipment (pumps, fans)
+ Energy Required for Dust Removal (conveyors, sluicing, trips to waste site)

Data for these calculations were obtained during site visits and were generally nameplate ratings. Power conversion efficiencies, where necessary, were estimated based on generic devices.

Emissions Reduction

Particulate emission reductions were calculated from particulate emissions determined by an EPA Method 5 either upstream or downstream of the control devices and estimated efficiencies of the control devices.

Utility Incremental Emissions

Incremental electric utility power plant emissions resulting from the power required to operate the pollution control devices were estimated assuming a 32 percent thermal power plant efficiency for generation, transmission, and distribution. The utility incremental emissions were calculated from emission factors (Ref. 10) in Table 19 using the fuel most likely to be burned by the electric utility. Particulates are the primary pollutant being controlled at the industrial sites.* However, all five criteria pollutants are emitted from a power plant. Therefore, the total criteria pollutant emission rate was taken as a measure of electric utility power plant emissions, recognizing that simple addition of the separate emission factors does not reflect the degree of hazard for each pollutant.

TABLE 19. POWER PLANT EMISSION FACTORS

Thermal Power Plant Fuel Type	Emission Factor (sum of NO_x, SO_x, CO, THC, and Particulate) ng/J	lb/10^6 Btu
Oil-Fired	393	0.913
Pulverized Coal-Fired	3150	7.323
Gas-Fired	313	0.729

*An exception to this was Site 5 (2645) where the venturi scrubber also acted as a control of SO_2 emissions resulting from the cofiring oil with wood.

The emissions reduction at the industrial plant and emissions produced at the electric utility power plant were used to calculate the relative effectiveness of the in-plant control device.

Energy Analysis

The value determined in Section 4 for recoverable energy for the combustion device was compared with the energy requirements of the pollution control device.

RESULTS

Energy Requirements for Pollution Control

The energy required for pollution control is presented in Table 20. The percentage of fuel heat input ranged from 0.2 percent to 2 percent with an average value of 0.84 percent.

Table 21 presents literature data (Ref. 11) for energy consumption. The results for the three multicyclone sites of 0.5 percent and 0.35 percent fall between the range given in Table 21 of 0.2 to 0.9 percent. The energy consumption of the ESP units of 0.7, 0.2 and 2 (average = 0.97 percent) is generally higher than the literature range of 0.1 to 0.3 percent. The multicyclone-venturi scrubber combination had 1.8 percent and 0.29 percent (average = 1 percent) and falls in the low end of the range given in Table 22. Resources were not available to investigate the differences between the literature data ranges and the data reported here.

In-Plant Emissions Comparison to Electric Utility Emissions

The in-plant emissions reduction was considerably greater than the emissions created at the power plant in every case. These results are shown in Table 22. The ratio of plant emissions reduced to power plant emissions ranged from a low of 7.3 to a high of 23,100. The results are correlated with the particulate reduction, kg/hr in Figure 2. The figure shows a good correlation with the equation

$$\log \frac{\text{Plant emiss. red.}}{\text{Power plant emissions}} = 0.274 \log \left(\text{Particulate Reduction}, \frac{kg}{h}\right)^{1.898}$$

Pollution Control Energy Comparison with Recoverable Energy

The results of the analysis of waste heat recovery potential compared to energy requirements for pollution control are shown in Table 23. The ratio of recoverable energy to pollution control energy ranged from 0 to 49.

In every case where the flue gas temperature was greater than the minimum practical temperature, the recoverable energy was considerably greater than the pollution control energy.

TABLE 20. ENERGY REQUIRED FOR POLLUTION CONTROL

Combustion Device	Site	Fuel	Fuel Heat Input MW	Pollution Control Equipment	Energy Required For Control			Energy Required For Control as a Percent of Fuel Heat Input %
					Indirect MW	Direct MW	Total MW	
Rotary Cement Kiln (Dry)	3	Coke & Natural Gas	69.9	Multiclone & Baghouse	0.110	0.715	0.825	1.2
Rotary Cement Kiln (Wet)	9-1A	Natural Gas	61.4	Electrostatic Precipitator	0.120	0.334	0.454	0.7
Wood-Bark Boiler	10/1	Wood-Bark & Natural Gas	75.3	Multiclone & Venturi Scrubber	0.240	1.119	1.359	1.8
Wood-Bark Boiler	13	Wood-Bark & Coal	25.5	Multiclone	0.058	0.075	0.133	0.5
Black Liquor Recovery Boiler	10/2	Black Liquor	140.3	Electrostatic Precipitator (Wet Bottom)	0.002	0.264	0.286	0.2
Carbon Monoxide (CO) Boiler	11	CO & Refinery Gas	94.9	Multiclone	--	0.439	0.439	0.5
Steel Open Hearth Furnace	14	No. 6 Oil & Natural Gas	30.3	Electrostatic Precipitator	--	--	0.612 (averaged)	2.0
Wood/Oil Boiler	5 (2645)	Wood-Bark/ Oil	78.0	Multicyclone and Venturi Scrubber	0.014	0.212	0.227	0.29
Wood/Coal Boiler	3 (2645)	Wood/Coal	29.4	Multicyclone	0.048	0.055	0.103	0.35
								0.84 (average)

TABLE 21. LITERATURE DATA ON CONTROL DEVICE ENERGY CONSUMPTION*

Device Type	Smallest Particle Collected, micrometers	ΔP, Inches, WG	Energy Requirement	
			kW/1000 cfm	% plant out
Multiple Cyclone	5	2 - 10	0.5 - 2	0.2 - 0.9
Cyclone	10	---	1.2	0.5
ESP	0.2	---	0.75	0.3
ESP	<0.1	0.5 - 0.5	0.2 - 0.6	0.1 - 0.3
ESP	---	---	---	0.1
Venturi Scrubber	---	---	---	1 - 2
Venturi Scrubber	1	10 - 15	2 - 10	0.9 - 4.3

*Reference 12

TABLE 22. EMISSIONS AT INDUSTRIAL SITE AND THERMAL POWER PLANT

Site No.	Combustion Device	Control Device(s)	Efficiency of Pollution Control Device (%)	Particulate Emissions[1] Before Control ng/J (lb/10^6Btu)	After Control ng/J (lb/10^6Btu)	Particulate Emissions Reduced by Controls kg/hr (lb/hr)	Energy[2] Required at Power Plant MW (10^6Btu/hr)	Emissions[3] Generated at Power Plant kg/hr (lb/hr)	Emissions Reduced / Emissions at Power Plant
3	Cement Kiln (Dry)	Multiclone & Baghouse	80 & 99.8	98814 (229.8)**	32.4 (0.092)**	24537 (53982)	2.6 (8.9)	3.7 (8.1)[a]	6631
9-1A	Cement Kiln (Wet)	Electrostatic Precipitator	99.6	9804 (22.8)*	39.2 (0.091)**	2157 (4746)	1.4 (4.8)	1.6 (3.5)[c]	1348
10/1	Wood/Bark Boiler	Multiclone & Venturi Scrubber	97.7 (overall)	1334 (3.1)*	30.7 (0.071)**	354 (778)	4.3 (14.7)	4.9 (10.7)[c]	72
10/2	Black Liquor Recovery Boiler	Electrostatic Precipitator	99.6	3701 (8.6)*	15.7 (0.036)*	1866 (4105)	0.9 (3.1)	1.0 (2.3)[c]	1866
11	CO Boiler	Multiclone	99.9	107300 (250)**	107.3 (0.250)*	36929 (81243)	1.4 (4.8)	1.6 (3.5)[c]	23100
13	Wood/Bark Boiler	Multiclone	98.0	6300 (14.5)**	126 (0.29)*	562 (1236)	0.5 (1.7)	5.7 (12.5)[b]	98.6
14	Open Hearth Furnace	Electrostatic Precipitator	99.0	1372 (3.2)*	13.72 (0.032)**	148 (326)	1.8 (6.1)	20.3 (44.7)[b]	7.3
3 (2645)	Wood/Bark Boiler	Multicyclone	98.0	4390 (10.0)*	87.8 (0.20)**	319.5 (703.6)	0.1 (0.35)	1.2 (2.6)	267
5 (2645)	Wood/Bark Boiler	Multicyclone & Venturi Scrubber	84.1	2317 (5.4)*	464 (1.1)**	336 (741)	0.43 (1.5)	4.86 (10.7)[b]	68.6

Notes: (1) Source of Particulate Data

* = measured field test
** = calculated using estimated efficiency (For Site 3, measured particulate was 19800 ng/J in duct between the two control devices)

(2) Energy Required at Power Plant = (Energy Supplied for Pollution Control)/[Efficiency of Generation, Transmission & Distribution (0.32)]

(3) Power Plant Emissions as per AP-42 (sum of NO_x, SO_x, CO, HC, and Particulate Emissions)

a) Oil-Fired 0.9127 lb/10^6 Btu
b) Coal-Fired 7.323 lb/10^6 Btu
c) Gas-Fired 0.7286 lb/10^6 Btu

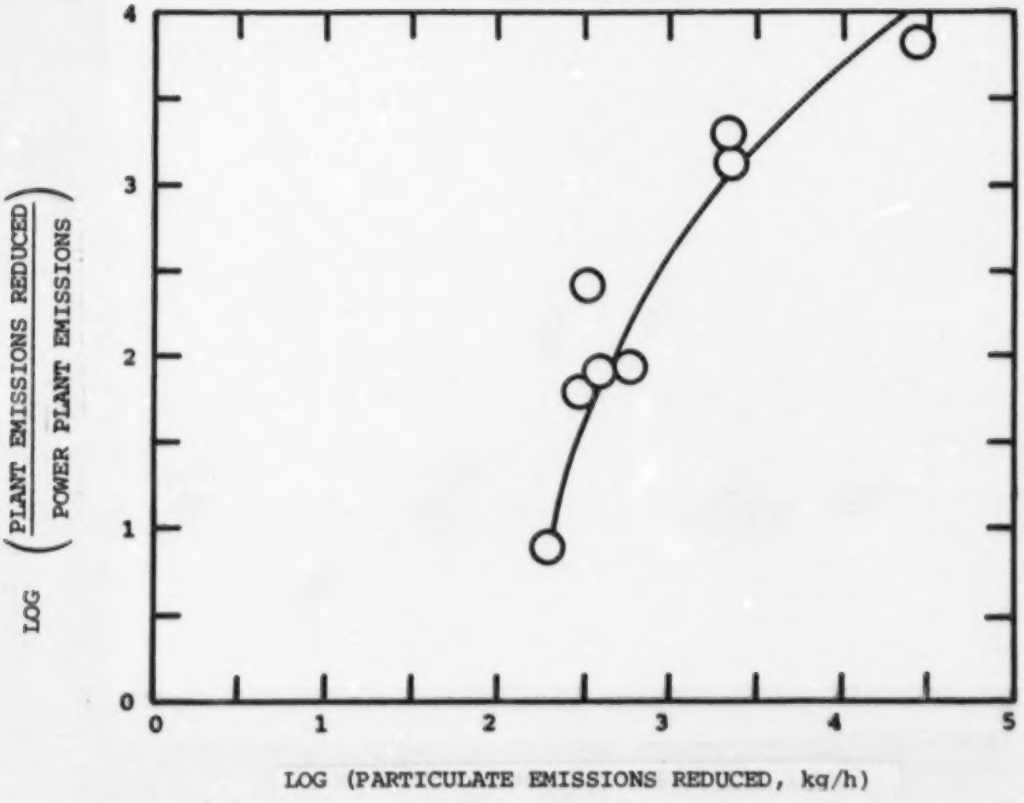

Figure 2. Variation of plant emissions reduced to utility emissions generated as a function of particulate reduction.

TABLE 23. COMPARISON OF RECOVERABLE ENERGY TO POLLUTION CONTROL ENERGY

Site	Combustion Device	Pollution Control Device	Fuel Heat Input, MW	Recoverable Energy, MW	Pollution Control Energy, MW	Recoverable Energy / Energy for Pollution Control
3	Cement Kiln (Dry)	Multicyclone & Baghouse	69.9	3.2	0.82	3.9
9-1A	Cement Kiln (Wet)	Electrostatic Precipitator	57.1	0.88	0.45	2.0
10/1	Wood/Bark Boiler	Multicyclone & Venturi Scrubber	75.3	7.5	1.36	5.5
10/2	Black Liquor Recovery Boiler	Electrostatic Precipitator	140.3	N/A	0.29	--
11	CO Boiler	Multicyclone	94.9	16.7	0.44	38
13	Wood/Bark Boiler	Multicyclone	25.5	1.2	0.13	9.2
14	Open Hearth Furnace	Electrostatic Precipitator	30.3	N/A	0.61	--
3 (2645)	Wood/Bark Boiler	Multicyclone	29.4	1.5	0.23	6.5
5 (2645)	Wood/Bark Boiler	Multicyclone & Venturi Scrubber	78	4.9	0.10	49

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APPENDIX A

SAMPLE CALCULATIONS

WASTE HEAT CONTENT

The sample calculations were performed in Engineering units. At the end of each particular section of calculations appropriate conversions to SI units are made.

Sample calculation for petroleum process heater (natural draft) Site 7/2, Test 1.

Sample port location: Heater outlet duct

Sample location dimensions: 6 ft diameter

Cross-sectional area of sample location: 28.32 sq ft

Fuel Data

Fuel: Refinery gas

Fuel Analysis: as shown on gaseous fuel analysis sheet

Fuel Higher Heating Value (HHV): 976.3 Btu/CF

Theoretical air flow rate: 9332 SCF air/10^6 Btu at 70 °F, 29.92 in. Hg, 0% excess air

Theoretical combustion products flow rate (dry): 8398 DSCF/10^6 Btu at 70 °F, 29.92 in. Hg, 0% excess air

Fuel flow: 53000 CFH

Fuel Heat input:

$$53{,}000 \text{ CFH} \times 976.3 \text{ Btu/CF} = 51.7 \times 10^6 \text{ Btu/hr} = 15.1 \text{ MW}$$

Combustion Air Data

Combustion air temperature = 95 °F

Excess air = 62.5%

Flow rate of combustion air to process heater:

$$= 9332 \frac{\text{SCF}}{10^6 \text{ Btu}} \times 51.7 \times 10^6 \frac{\text{Btu}}{\text{hr}} \times 1.63 \frac{\text{Actual air}}{\text{Theor. air}} \times \frac{555 \text{ °R}}{530 \text{ °R}} \times \frac{1 \text{ hr}}{60 \text{ min}}$$

$$= 13725 \text{ ACFM}$$

HP-67 KEYED CALCULATION SHEET

GASEOUS FUEL ANALYSIS

Test No. 7/2-1

Test No. _____ Date 7/19/76 Location _____

Unit No. Ref. Htr. #2 Fuel Ref. Gas Fuel Sample No. _____

Fuel Sample Point _____ Fuel Analysis by G.C. Anal.

Gas		% Volume		
CH_4	Methane	53.2	[STO]	[0]
C_2H_6	Ethane	4.9	[STO]	[1]
C_3H_8	Propane	4.3	[STO]	[2]
C_4H_{10}	Butane	1.5	[STO]	[3]
C_5H_{12}	Pentane		[STO]	[4]
C_2H_4	Ethylene	0.8	[STO]	[5]
C_3H_6	Propylene	3.2	[STO]	[6]
C_4H_8	Butylene	0.1	[STO]	[7]
C_5H_{10}	Pentylene	0.6	[STO]	[8]
C_2H_2	Acetylene		[STO]	[9]
			[f]	[P≷S]
C_6H_6	Benzene		[STO]	[0]
O_2	Oxygen		[STO]	[1]
N_2	Nitrogen	2.4	[STO]	[2]
CO_2	Carb. Diox.	0.8	[STO]	[3]
CO	Carb. Monox.		[STO]	[4]
H_2	Hydrogen	28.2	[STO]	[5]
			[f]	[P≷S]

Load "Gaseous Fuel Analysis I"

[A] Σ % Volume = 100.0

$\frac{\text{CF Air}}{\text{CF Fuel}}$ = 9.11

[B] $\frac{\text{Btu (HHV)}}{\text{CF Fuel}}$ = 976.3

[C] $\frac{\text{CF } CO_2}{\text{CF Fuel}}$ = 0.973

Load "Gaseous Fuel Analysis II"

[D] $\frac{\text{CF } H_2O}{\text{CF Fuel}}$ = 1.886

[E] $\frac{\text{CF Prod}}{\text{CF Fuel}}$ = 10.086

[A] $\frac{\text{lb Prod}}{\text{CF Fuel}}$ = 0.043

Load "Gaseous Fuel Analysis III"

[B] $\frac{\text{SCF Air}}{10^6 \text{ Btu}}$ = 9332 at 70 °F, 29.92 in. Hg

[R/S] $\frac{\text{WSCF Prod}}{10^6 \text{ Btu}}$ = 10330

[R/S] % Moisture = 18.70

[R/S] $\frac{\text{DSCF Prod}}{10^6 \text{ Btu}}$ = 8398

[R/S] % CO_2, dry = 11.87

[R/S] K = _____ } NO_x

[R/S] K' = _____ }

[R/S] K = _____ } CO

[R/S] K' = _____ }

[R/S] K = _____ } HC

[R/S] K' = _____ }

[R/S] K = _____ } SO_x

[R/S] K' = _____ }

$lb/10^6$ Btu = (ppm at 3% O_2)/K

ng/J = (ppm at 3% O_2)/K'

Mass flow rate of combustion air at 95 °F, 29.92 in. Hg, 62.5% excess air

$$= 13725 \text{ ACFM} \times 2116 \frac{\text{lb}_f}{\text{ft}^2} \times \frac{\text{lb}_m - °\text{R}}{53.55 \text{ ft-lb}_f} \times \frac{1}{555 °\text{R}} \times \frac{\text{min}}{60 \text{ sec}}$$

$$= 16.3 \text{ lb}_m/\text{sec} = 7.4 \text{ kg/s}$$

Mass flow rate of refinery gas fuel at 95 °F, 29.92 in. Hg

$$= 53000 \text{ SCFH} \times \frac{555 °\text{R}}{530 °\text{R}} \times 2116 \frac{\text{lb}_f}{\text{ft}^2} \times \frac{\text{lb}_m - °\text{R}}{94.09 \text{ ft-lb}_f} \times \frac{1}{555 °\text{R}} \times \frac{\text{hr}}{3600 \text{ sec}}$$

$$= 0.62 \text{ lb}_m/\text{sec} = 0.28 \text{ kg/s}$$

Air specific heat at constant pressure = $C_{p_{air}}$ = 0.255 Btu/lb_m-°F = 1065 J/kg K

Flue Gas Data

Mass flow rate of flue gas = Mass flow rate of combustion air
+ Mass flow rate of refinery gas fuel
(assuming no infiltration of ambient air)
= 16.9 lb_m/sec = 7.7 kg/s

Flue gas composition:

Component	Volume, % Dry Basis	Wet Basis
H_2O	--	13.2
CO_2	7.0	6.1
CO	0	0
O_2	8.5	7.4
N_2	84.5	73.3
Molecular Weight	29.46	27.95

Flue gas temperature: 945 °F = 1405 °R

Flue gas pressure: 30.22 in. Hg

Flue gas volumetric flow rate at 945 °F and 30.22 in. Hg

= mass flow rate/flue gas density

$$= \frac{16.9\ lb_m/sec \times 60\ sec/min}{[2116 \times (30.22/29.92)\ \frac{lb_f}{ft^2} \Big/ 55.28\ \frac{ft\text{-}lb_f}{lb_m\text{-}°R} \times 1405\ °R]}$$

= 35,848 ACFM

Waste heat content at flue gas temperature, T_s, referenced to 77°F (298 K) is calculated from the following equation:

$$\left[\left[\sum_i \left[\frac{Btu}{lb\text{-}mole_i} \cdot (x_i)\right]_{at\ T_s}\right] - \left[\sum_i \left[\frac{Btu}{lb\text{-}mole_i} \cdot (x_i)\right]_{77}\right] + \left[x_{H_2O} \cdot \frac{18900\ Btu}{lb\text{-}mole\ water}\right]\right]$$

$\cdot$ [1/(ACF/lb-mole)] $\cdot$ ACFH

This equation assumes that the flue gas composition (x_i) is not a function of temperature below T_s.

Flue Gas Composition*	I Volume Factor (wet) x_i	II $\frac{Btu}{lb\text{-}mole}$ at 945°F	III I x II $\left(\frac{Btu}{lb\text{-}mole}\right) x_i$ at 945 °F	IV $\frac{Btu}{lb\text{-}mole}$ at 77°F	V (I x IV) $\left(\frac{Btu}{lb\text{-}mole}\right) x_i$	VI $x_{H_2O} \cdot 18900$
H_2O	0.132	11668	1540.2	4258	562.1	2494.8
CO_2	0.061	13402	817.5	4030	245.8	
O_2	0.074	10248	758.4	3725	275.7	
N_2	0.733	9932	7280.2	3729	2733.4	
$\Sigma \frac{Btu}{lb\text{-}mole}$			10396.2		3816.9	2494.8

*SO_2 and NO in trace quantities - not included.

Waste heat content of the flue gas (referenced to 77°F) =

$$[10396.2 - 3816.9 + 2494.8]\frac{\text{Btu}}{\text{lb-mole}} \cdot \frac{1 \text{ lb-mole}}{386.9 \frac{\text{SCF}}{\text{lb-mole}} \cdot \frac{1405}{530} \frac{\text{ACF}}{\text{SCF}}} \cdot 36848 \text{ ACFM} \cdot 60 \frac{\text{min}}{\text{hr}}$$

$= 19.6 \times 10^6$ Btu/hr = 5.8 MW

Waste heat content as percent of fuel heat input

= 5.8 MW/15.1 MW x 100 = 38.4%

Percent recoverable energy as non-condensible is calculated from the relationship:

$$\frac{\left[\sum_i \left[\frac{\text{Btu}}{\text{mole}_i} \cdot x_i\right]_{T_s} - \sum_i \left[\frac{\text{Btu}}{\text{mole}_i} \cdot x_i\right]_{77\ °F}\right] \cdot 100}{\left[\sum_i \left[\frac{\text{Btu}}{\text{mole}_i} \cdot x_i\right]_{T_s} - \sum_i \left[\frac{\text{Btu}}{\text{mole}_i} \cdot x_i\right]_{77\ °F} + [x_{H_2O} \cdot 18900]\right]}$$

For this case, 7/2-1, percent recoverable energy as non-condensible

$$= \frac{[10396.2 - 3816.9] \cdot 100}{[10396.2 - 3816.9 + 2494.8]}$$

= 72.5%

Specific heat of flue gas, C_{pg}, is calculated from the relationship

$$\frac{\left[\sum_i \left[\frac{\text{Btu}}{\text{mole}_i} \cdot x_i\right]_{T_s} - \sum \left[\frac{\text{Btu}}{\text{mole}_i} \cdot x_i\right]_{77\ °F} \quad \frac{\text{Btu}}{\text{lb °F}}\right]}{[T_s - 77] \cdot \text{MW}}$$

$$= \frac{[10396.2 - 3816.9]}{[945 - 77] \cdot 27.95}$$

= 0.27 Btu/lb °F = 1.13×10^3 J/kg K

APPENDIX B

ENERGY RECOVERY OPTION ANALYSIS

ENERGY RECOVERY TABLE EXPLANATION

The Energy Recovery Calculations were performed with the VisiCalc® microcomputer software program. The tables following this table show the formulas used in the calculations. Table 24 is an explanation of the nomenclature used. In Table 25 three columns are reproduced from the first data table (for process heaters,) labeled A, B, and C. The column headed "Input Data and Formulas" shows the values that were input and the formulas used to calculate the remaining values.

In Table 25, the first column, labeled A, contains row numbers which are used to designate the values for each calculation in each column. For example, Row 12 shows the formula +C11*C10. This means to obtain the value in Column C, Row 11 and multiply it by the value of Column C, Row 10.

The formulas shown are of two types:

1. Those beginning with +
2. Those beginning with @IF

For those beginning the +, the formulas are simple arithmetic calculations using either Column-Row References (preceded by a letter (C) or absolute values (no preceding letter). For example, Row 22 shows the formula +C21*C16/1000. This means to obtain the value in Column C, Row 21 (=132), multiply it by the value in Column C, Row 16 (=16.01), then divide by 1000. The result of the calculation is then placed in Column C, Row 22 (2.11).

Formulas beginning with @IF involve decision calculations producing branched calculations dependent on the magnitudes of specific values input or calculated in rows above the row containing the @IF formula. As an example, consider Row 20 which contains the formula:

@IF(C19>400,C19,400)

This formula involves IF...THEN...ELSE logic, meaning:

IF (Value in Column C Row 19 is greater than 400,
THEN put the value from Column C Row 19 in Column C Row 20,
ELSE put the value 400 in Column C Row 20)

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TABLE 24. WASTE ENERGY RECOVERY TABLE NOMENCLATURE

PROCESS HEATERS		
2	EX APH?	=0, no existing air preheat, =1 with existing air preheat
3	QIN, MW	Fuel heat input, MW
4	TAI, K	Inlet air temperature, K
5	TGI, K	Inlet stack gas temperature, K
6	WA, KG/S	Air flow, kg/s
7	CPA	Air specific heat, kJ/kg-K
8	WG, KG/S	Gas flow, kg/s
9	CPG	Gas specific heat, kJ/kg-K
10	TGI-TAI	Maximum gas-air temperature differential, K
11	EFF	Heat exchanger effectiveness, input for initial estimate
12	E(TGI-TAI	Air temperature rise in heat exchanger, K
13	TAO OUT.7	Heat exchanger air outlet temperature, K
14	AIR BP FC	Heat exchanger air bypass factor
15	WA*CPA*BF	(Air flow) (specific heat) (air bypass factor)
16	WG*CPG	(Gas flow) (specific heat)
17	WCA/WCG	Ratio of air/gas flow x specific heat
18	W/W.E.DT	Gas temperature drop in heat exchanger
19	TGO OUT.7	Gas temp. out of heat exchanger at input effectiveness (row 11)
20	TGO ACT	Gas temperature from row above or 400K, which ever is higher
21	TGI-TGOAC	Actual gas temperature drop
22	QREC, MW	Air preheater recoverable energy, MW
23	TAO-TAI	Actual air temperature rise, K
24	TAO ACT	Actual air outlet temperature, K
25	EFFEC	Actual heat exchanger effectiveness
26	Q/QIN, %	Recoverable energy as percent of fuel heat input
27	FUEL $	Input cost of fuel per unit heat value, $/MW-h
28	COST $K	Installed cost of air preheater, $1,000
29	SAVE $K	Annual fuel savings, $1,000
30	---------	
31	TGO-400	Process heat option gas temperature drop, K
32	QREC MW	Recoverable energy by process heat option, MW
33	Q/QIN %	Recoverable energy as percent of fuel input
34	COST $K	Installed cost of process heat exchanger, $1,000
35	SAVE $K	Annual fuel savings, $1,000
36	---------	
37	TGO-416	Heat engine cycle gas temperature drop, K
38	QELEC MW	Recoverable energy of heat engine, MW
39	Q/QIN %	Recoverable energy as percent of fuel input
40	COST $K	Installed cost of heat engine cycle, $1,000
41	SAVE $K	Annual fuel savings, $1,000

TABLE 25. WASTE ENERGY RECOVERY CALCULATION FORMULAS

/---A----/	---B----/	---C----/	Input Data And Formulas
PROCESS	HEATERS	4-4	4-4
2	EX APH?	0	0
3	QIN, MW	30.9	30.9
4	TAI, K	294	294
5	TGI, K	550	550
6	WA, KG/S	11.7	11.7
7	CPA	1.005	1.005
8	WG, KG/S	14.17	14.17
9	CPG	1.13	1.13
10	TGI-TAI	256	256
11	EFF	.7	.7
12	E(TGI-TAI	179	+C11*C10
13	TAO OUT.7	473	+C12+C4
14	AIR BP FC	1	1
15	WA*CPA*BF	11.76	+C6*C7*C14
16	WG*CPG	16.01	+C8*C9
17	WCA/WCG	0.73	+C15/C16
18	W/W.E.DT	131.60	+C17*C12
19	TGO OUT.7	418	+C5-C18
20	TGO ACT	418	@IF(C19>400,C19,400)
21	TGI-TGOAC	132	+C5-C20
22	QREC, MW	2.11	+C21*C16/1000
23	TAO-TAI	179	+C22*1000/C15
24	TAO ACT	473	+C23+C4
25	EFFEC	0.70	+C23/C10
26	Q/QIN, %	6.82	+C22/C3*100
27	FUEL $	17	17
28	COST $K	360	@IF(C22>.5,C3^.6*46,@NA)
29	SAVE $K	287	@IF(C22>.5,+C22*8*C27,@NA)
30	----------	----------	---------
31	TGO-400	150	@IF(C2>0,@IF(C20>400,C20-400,@NA),@IF(C5>400,+C5-400,@NA
32	QREC MW	2.40	+C16*C31/1000
33	Q/QIN %	7.77	+C32/C3*100
34	COST $K	187	@IF(C32>.5,37*C32+(67*(C32^.44)),@NA)
35	SAVE $K	327	@IF(C32>.5,+C32*8*C27,@NA
36	----------	----------	---------
37	TGO-416	134	@IF(C2>0,@IF(C20>533,C20-416,@NA),@IF(C5>533,C5-416,@NA
38	QELEC MW	0.47	+C16*C37*.22/1000
39	Q/QIN %	1.53	+C38/C3*100
40	COST $K	NA	@IF(C38>.5,C38*2000,@NA)
41	SAVE $K	NA	@IF(C38>.5,C38*8000*.08,@NA)

Note that in Row 31, a multiple @IF statement is used to extend the range of the decisions.

In some of the @IF formulas, a @NA appears. This function is used to terminate an IF...THEN...ELSE logic path and enter the letters "NA" to indicate that calculation is Not Applicable, as, for example, when the recovered energy is less than 0.5 MW, then cost calculations are not applicable.

Tables 26-28 present the complete calculations for all devices.

TABLE 26. WASTE ENERGY RECOVERY CALCULATIONS - PROCESS HEATERS

PROCESS	HEATERS	4-4	4-6	5/1-1	5/2-1	7/1-1	7/2-1	7-2-2	7-5-1	12/1-1	12/1-8	12/2-1	12/2-2
2	EX APH?	0	0	0	0	0	0	0	0	1	1	0	0
3	QIN, MW	30.9	31.1	18.5	10.1	15.5	15.1	15.9	14.3	22.5	22.5	10.2	10.2
4	TAI, K	294	294	291	297	303	303	299	302	291	291	316	316
5	TGI, K	550	557	478	481	592	780	693	687	915	876	563	556
6	WA, KG/S	11.7	11.8	7	3.7	7.1	7.4	6.32	5.97	7.5	8.3	3.6	4.1
7	CPA	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005
8	WG, KG/S	14.17	12.54	7.62	3.8	7.66	7.7	6.62	6.25	7.94	8.97	4.38	4.4
9	CPG	1.13	1.17	1.13	1.09	1.13	1.13	1.13	1.13	1.13	1.04	1.17	1.13
10	TGI-TAI	256	263	187	184	289	477	394	385	624	585	247	240
11	EFF	.7	.7	.7	.7	.7	.7	.7	.7	.59	.63	.7	.7
12	E(TGI-TAI	179	184	131	129	202	334	276	270	368	369	173	168
13	TAO OUT.7	473	478	422	426	505	637	575	572	659	660	489	484
14	AIR BP FC	1	1	1	1	1	1	1	1	1	1	1	1
15	WA*CPA*BF	11.76	11.86	7.04	3.72	7.14	7.44	6.35	6.00	7.54	8.34	3.62	4.12
16	WG*CPG	16.01	14.67	8.61	4.14	8.66	8.70	7.48	7.06	8.97	9.33	5.12	4.97
17	MCA/MCG	0.73	0.81	0.82	0.90	0.82	0.85	0.85	0.85	0.84	0.89	0.71	0.83
18	W/W.E.BT	131.60	148.81	106.95	115.63	166.77	285.39	234.18	228.95	309.29	329.55	122.07	139.23
19	TGO OUT.7	418	408	371	365	425	495	459	458	606	546	441	417
20	TGO ACT	418	408	400	400	425	495	459	458	606	546	441	417
21	TGI-TGOAC	132	149	78	81	167	285	234	229	309	330	122	139
22	QREC, MW	2.11	2.18	0.67	0.34	1.44	2.48	1.75	1.62	2.78	3.07	0.63	0.69
23	TAO-TAI	179	184	95	90	202	334	276	269	368	369	173	168
24	TAO ACT	473	478	386	387	505	637	575	571	659	660	489	484
25	EFFEC	0.70	0.70	0.51	0.49	0.70	0.70	0.70	0.70	0.59	0.63	0.70	0.70
26	Q/QIN, %	6.82	7.02	3.63	3.32	9.31	16.45	11.02	11.31	12.33	13.66	6.13	6.79
27	FUEL $	17	17	17	17	17	17	17	17	17	17	17	17
28	COST $K	360	362	265	NA	238	235	242	227	298	298	185	185
29	SAVE $K	287	297	91	NA	196	338	238	220	377	418	85	150
30													
31	TGO-400	150	157	78	81	192	380	293	287	206	146	163	156
32	QREC MW	2.40	2.30	0.67	0.34	1.66	3.31	2.19	2.03	1.85	1.37	0.84	0.78
33	Q/QIN %	7.77	7.41	3.63	3.32	10.72	21.90	13.79	14.17	8.20	6.07	8.19	7.60
34	COST $K	187	182	81	NA	145	236	176	166	156	127	93	89
35	SAVE $K	327	313	91	NA	226	450	298	276	251	186	114	168
36													
37	TGO-416	134	141	NA	NA	176	364	277	271	190	130	147	140
38	QELEC MW	0.47	0.46	NA	NA	0.34	0.70	0.46	0.42	0.37	0.27	0.17	0.15
39	Q/QIN %	1.53	1.46	NA	NA	2.16	4.61	2.87	2.94	1.66	1.19	1.62	1.50
40	COST $K	NA	NA	NA	NA	NA	1394	NA	NA	NA	NA	NA	NA
41	SAVE $K	NA	NA	NA	NA	NA	446	NA	NA	NA	NA	NA	NA

TABLE 27. WASTE ENERGY RECOVERY CALCULATIONS - KILNS & METAL FURNACES

	KILNS	1-1	3-2	9-1A	9-(2645)	6-(2645)
2	EX APWT	0	0	0	0	0
3	QIN, MM	12.4	69.9	61.4	57.1	15.6
4	TAI, F	305	672	672	1144	1402
5	TGI, F	330	558	422	455	527
6	MA, KG/S	5	24.9	25.8	33.9	9.36
7	CPA	1.005	1.005	1.005	1.005	1.005
8	MG, KG/S	18.67	19.52	36.83	35.9	9.75
9	CPG	1	1.04	1.09	1.09	1.1
10	TGI-TAI	25	-114	-250	-689	-875
11	EFF	NA	NA	NA	NA	NA
12	E(TGI-TAI	NA	NA	NA	NA	NA
13	TAO OUT.7	NA	NA	NA	NA	NA
14	AIR BP FC	1	1	1	1	1
15	MA*CPA*BF	5.03	25.02	25.93	34.07	9.41
16	MG*CPG	18.67	20.30	40.14	39.13	10.73
17	MCA/MCG	0.27	1.23	0.65	0.87	0.88
18	M/M.E.DT	NA	NA	NA	NA	NA
19	TGO OUT.7	NA	NA	NA	NA	NA
20	TGO ACT	NA	NA	NA	NA	NA
21	TGI-TGOAC	NA	NA	NA	NA	NA
22	QREC, MM	NA	NA	NA	NA	NA
23	TAO-TAI	NA	NA	NA	NA	NA
24	TAO ACT	NA	NA	NA	NA	NA
25	EFFEC	NA	NA	NA	NA	NA
26	Q/QIN, %	NA	NA	NA	NA	NA
27	FUEL $	17	17	17	10	27
28	COST $K	NA	NA	NA	NA	NA
29	SAVE $K	NA	NA	NA	NA	NA
30						
31	TGO-400	NA	158	22	55	127
32	QREC MM	NA	3.21	0.88	2.15	1.36
33	Q/QIN %	NA	4.59	1.44	3.77	8.73
34	COST $K	NA	221	96	174	127
35	SAVE $K	NA	436	120	172	294
36						
37	TGO-416	NA	142	NA	NA	NA
38	QELEC MM	NA	0.63	NA	NA	NA
39	Q/QIN %	NA	0.91	NA	NA	NA
40	COST $K	NA	1268	NA	NA	NA
41	SAVE $K	NA	406	NA	NA	NA

	METALS	6-1	6-3	14-1	16/1-17	16/2-1
	EX APWT	0	0	1	0	0
	QIN, MM	6.5	7.1	30.3	24.6	2.3
	TAI, F	311	303	1339	311	311
	TGI, F	1211	1208	550	730	1543
	MA, KG/S	2.4	3.4	29.6	8.9	1.1
	CPA	1.005	1.005	1.005	1.005	1.005
	MG, KG/S	2.73	3.61	34.79	23.47	1.1
	CPG	1.25	1.17	1.13	1.09	1.34
	TGI-TAI	900	905	-789	419	1272
	EFF	.7	.7	NA	.7	.7
	E(TGI-TAI	630	634	NA	293	890
	TAO OUT.7	941	937	NA	604	1201
	AIR BP FC	1	1	1	1	1
	MA*CPA*BF	2.41	3.42	29.75	8.94	1.11
	MG*CPG	3.41	4.22	39.31	25.58	1.47
	MCA/MCG	0.71	0.81	0.76	0.35	0.75
	M/M.E.DT	445.29	512.51	NA	102.55	647.80
	TGO OUT.7	766	695	NA	627	915
	TGO ACT	766	695	NA	627	915
	TGI-TGOAC	445	513	NA	103	668
	QREC, MM	1.52	2.16	NA	2.62	0.98
	TAO-TAI	630	633	NA	293	890
	TAO ACT	941	936	NA	604	1201
	EFFEC	0.70	0.70	NA	0.70	0.70
	Q/QIN, %	23.38	30.49	NA	10.66	42.80
	FUEL $	17	27	17	17	17
	COST $K	141	149	NA	314	76
	SAVE $K	207	468	NA	257	134
	TGO-400	811	808	NA	330	1183
	QREC MM	2.77	3.41	NA	8.44	1.74
	Q/QIN %	42.58	48.07	NA	34.32	75.81
	COST $K	207	241	NA	484	150
	SAVE $K	376	737	NA	1148	237
	TGO-416	795	792	NA	314	1147
	QELEC MM	0.60	0.74	NA	1.77	0.38
	Q/QIN %	9.18	10.37	NA	7.18	16.45
	COST $K	1194	1472	NA	2534	NA
	SAVE $K	382	471	NA	1131	NA

TABLE 28. WASTE ENERGY RECOVERY CALCULATIONS - BOILERS

	BOILERS	10/1-1	10/2-1	13-6	11-1	19-53	19-97	19-101	200C-2	200-24	3-10	5-1-1
2	EX APWT	1	1	1	0	0	0	0	1	1	1	1
3	QIN, MJ	75.3	140.3	25.5	94.9	5	5.8	5.7	11.7	11.2	29.4	78
4	TAI, K	317	302	291	311	294	294	294	288	294	303	338
5	TGI, K	648	683	550	589	543	527	537	617	616	569	664
6	MA, KG/S	41.7	46	13.8	31.3	1.8	2.2	1.6	3.9	4.1	12.98	30.78
7	CPA	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005
8	MG, KG/S	49.92	57.58	15.17	78.28	2.03	2.27	1.77	3.81	4.35	14.89	28.92
9	CPG	1.13	1.17	1.04	1.13	1.09	1.09	1.17	1.04	1.04	1.12	1.11
10	TGI-TAI	331	381	259	278	249	233	243	329	322	266	326
11	EFF	.79	NA	.753	.7	.7	.7	.7	.377	.379	.7	.67
12	E(TGI-TAI	261	NA	195	195	174	163	170	124	122	186	218
13	TAO CUT.7	578	NA	486	506	468	457	464	412	416	489	556
14	AIR HP FC	.593	1	.42	1	1	1	1	.986	1.124	.55	.97
15	MA*CP*MBF	24.85	46.23	5.82	31.46	1.81	2.21	1.61	3.86	4.63	7.17	30.01
16	MG*CPG	56.41	67.37	15.78	88.46	2.21	2.47	2.07	3.96	4.52	16.68	43.20
17	MCA/MCG	0.44	0.69	0.37	0.36	0.82	0.89	0.78	0.98	1.02	0.43	0.69
18	M/M.E.DT	115.20	NA	72.01	69.20	142.50	145.74	132.08	120.97	124.94	80.11	151.71
19	TGO CUT.7	533	NA	478	520	401	381	405	496	491	489	512
20	TGO ACT	533	NA	478	520	401	400	405	496	491	489	512
21	TGI-TGOAC	115	NA	72	69	142	127	132	121	125	80	152
22	QREC, MJ	6.50	NA	1.14	6.12	0.32	0.31	0.27	0.48	0.57	1.34	6.35
23	TAO-TAI	261	NA	195	195	174	142	170	124	122	186	218
24	TAO ACT	578	NA	486	506	468	436	464	412	416	489	556
25	EFFEC	0.79	NA	0.75	0.70	0.70	0.61	0.70	0.38	0.38	0.70	0.67
26	Q/QIN, %	8.63	NA	4.46	6.45	6.31	5.42	4.80	4.10	5.05	4.54	8.40
27	FUEL $	17	17	10	17	27	27	27	27	27	10	27
28	COST $K	615	NA	321	707	NA	NA	NA	NA	196	350	628
29	SAVE $K	884	NA	91	833	NA	NA	NA	NA	122	107	1416
30												
31	TGO-400	133	NA	78	189	143	127	137	96	91	89	112
32	QREC MJ	7.49	NA	1.23	16.72	0.32	0.31	0.28	0.38	0.41	1.48	4.85
33	Q/QIN %	9.95	NA	4.83	17.62	6.33	5.42	4.98	3.25	3.68	5.04	6.22
34	COST $K	440	NA	119	850	NA	NA	NA	NA	NA	125	314
35	SAVE $K	1019	NA	98	2274	NA	NA	NA	NA	NA	119	1048
36												
37	TGO-416	NA	NA	NA	173	127	NA	121	NA	NA	NA	NA
38	QELEC MJ	NA	NA	NA	3.37	0.06	NA	0.06	NA	NA	NA	NA
39	Q/QIN %	NA	NA	NA	3.55	1.24	NA	0.97	NA	NA	NA	NA
40	COST $K	NA	NA	NA	6733	NA	NA	NA	NA	NA	NA	NA
41	SAVE $K	NA	NA	NA	2135	NA	NA	NA	NA	NA	NA	NA